PB85-117091

Feasibility of Using Chemical Liners for Landfilling Electroplating Sludges

SCS Engineers, Inc., Long Beach, CA

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Nov 84

U.S. Department of Commerce
National Technical Information Service
NTIS

PB85-117091

EPA-600/2-84-171
November 1984

FEASIBILITY OF USING CHEMICAL LINERS FOR LANDFILLING ELECTROPLATING SLUDGES

by

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Contract No. 68-01-5059

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NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-84-171	2.	3. RECIPIENT'S ACCESSION NO. PB85 117091
4. TITLE AND SUBTITLE Feasibility of Using Chemical Liners for Landfilling Electroplating Sludges		5. REPORT DATE November 1984
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) H. Tan Phung, S. P. Shelton, P. Pagoria, K. V. LaConde		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS SCS Engineers, Inc. 4014 Long Beach Boulevard Long Beach, California 90807		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. 68-01-5059
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory- Cin., OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Final
		14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES

Robert E. Landreth, Project Officer (513-684-7836)

16. ABSTRACT

Seven (7) test cells, each measuring 24 m (8 ft) square and 1.8 m (6 ft) deep, were constructed in native soil at a segregated monolandfill to determine whether electroplating sludges could be stored for possible future metals recovery. Two cells each (replicates) were lined with fly ash; two with hydrous oxides of iron; two with agricultural limestone; the control was lined with native bank sand. All cells were filled with approximately the same mix of sludge (about 10,000 kg).

A leachate collection and monitoring program was initiated. Natural rainfall was the only liquid added during the 30 months of field evaluation. Leachate volume, pH, EC, Cr(VI), Cr(III), Cd, Cu, Fe, Mn, Ni, Pb, and Zn were analyzed on a monthly basis. Se, cyanide, B, and Hg were examined on a less frequent basis.

No significant leaching of heavy metals was observed. The excavated sludges exhibited chemical and physical characteristics similar to the raw sludges originally deposited, thus indicating that future recovery of metals is possible. A cost analysis was performed for full-scale chemical waste landfills utilizing each of the liner materials.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES 95
	20. SECURITY CLASS *(This page)*	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

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SECTION 1

SUMMARY

EPA contracted with SCS Engineers to evaluate various chemical liners that might be used in a segregated monolandfill for the disposal of electroplating wastewater sludges.

A test site was selected in an unused portion of a secure landfill in South Carolina. Seven cells were constructed; each was 2.4 m (8 ft) square and 1.8 m (6 ft) deep. One cell was reserved as a control and the other six were designated as replicate test cells.

Fly ash, agricultural limestone, and hydrous oxides of iron were each used to line two test cells; the control cell was lined with sand. Crushed limestone is commonly used to neutralize acidic agricultural soils. As a test liner, it was expected to neutralize or retard the formation of acidic leachates which might mobilize cationic metal species. Limestone has been used in such applications at several sludge disposal sites, but little field research has been done to confirm its expected utility. It was therefore included as a test liner in this study.

Hydrous iron oxides were recommended for field trial as a sludge disposal liner because of their established role as scavengers of heavy metals in soils and water. They are, in addition, inexpensive and readily available. These factors combined to make iron oxides an attractive second test liner.

Basic fly ash is a by-product of burning coal for energy production and is therefore widely available as a waste product. It contains lime and iron oxides, which retain trace metals, and tends to be basic, which favors attenuation of most heavy metals. Despite its potential as an attenuating liner, fly ash has not been extensively studied for this application. It was, therefore, considered an ideal candidate for these field tests.

All seven cells were filled with sludges from the treatment of electroplating wastewaters. Leachate was collected under a CO_2 environment from below the cells approximately once a month for 2-1/2 years and analyzed to evaluate the capacity of the liners to retain heavy metals leached from the sludges. Each sample was analyzed for pH, electrical conductivity (EC), cyanide, boron, arsenic, selenium, mercury, chromium(III), chromium(VI), cadmium, nickel, copper, iron, manganese, lead, and zinc.

After the last leachate samples were collected in August 1982, each cell was core sampled to assess the vertical distribution of selected metals in the sludge, the liner, and the soils.

The concentrations of metals and soluble salts in the leachate varied widely during the first 12 to 15 months and then leveled off. The concentrations of the various metals did not appear to be related to the concentrations found in the sludges. The volume of leachate collected was indicative of the permeabilities of the liners used in the test cells; no correlation was apparent between the leachate volumes and rainfall data.

Liners comprised of limestone and hydrous oxides of iron appeared to retain more metals than did fly ash, but no significant leaching was observed in any of the test cells. The excavated sludges exhibited characteristics similar to the raw sludges originally deposited. Because only small amounts of metals were leached from the sludges, the overall relative performance of the liners cannot be judged from this study.

From an economic standpoint, hydrous oxides of iron (derived from ferric sulfate) would likely be prohibitively expensive for this application.

Additional studies will be needed before chemical liners can be applied to full-scale landfilling of metal-finishing sludges. The studies may include:

- The arrangement and thickness of different materials in the cell with respect to maximum metal retention.
- The leachability of heavy metals in electroplating sludges of lower pH than those used in this study.
- Protection for and stability of side slopes in landfill cells lined with chemical liners.
- Assess permeabilities of various liner materials under placement (compaction) and chemical conditions.

SECTION 2

INTRODUCTION

The metal finishing industry generates a variety of wastewater streams containing acids, cyanides, hexavalent chromium, and other heavy metals. These wastewater streams are generally treated separately to remove hazardous constituents, or to convert them to less hazardous species. Continued emphasis on wastewater treatment and reduced effluent discharges are expected to increase the future amounts of treatment sludges generated.

Several relatively new hazardous waste management technologies (e.g., chemical fixation, encapsulation, metal recovery) have been proposed for electroplating sludges, but none is sufficiently developed to be used on a wide scale. The prevalent disposal method has been to bury the sludge in a sanitary landfill (past practice), or in a segregated, secure landfill.

In 1978, as part of the regulatory effort under Section 3004 of the Resource Conservation and Recovery Act of 1976 (RCRA), the U.S. Environmental Protection Agency's (U.S. EPA) Office of Solid Waste directed specific studies on technologies for the disposal and recovery of electroplating sludges. Since these sludges have potential for metal recovery in future years, emphasis was placed on developing environmentally acceptable, cost-effective disposal methods to facilitate potential recovery. The approach utilized in this study tested selected inexpensive yet promising chemical liners which could be used in a segregated monolandfill. The liner concept here is not related to reduced permeability; rather, the chemical liner was to serve as a filter for hazardous constituents, particularly heavy metals. These metals would be retained either in the metal sludge or in the liner, so that they could be retrieved once recovery technology proved both cost effective and environmentally sound.

Under contract to EPA, SCS Engineers performed a field study. The objectives were to:

- Determine the effectiveness of using various inexpensive or waste materials to line disposal sites for metal hydroxide sludges.

- Prepare a conceptual design (including cost estimates) of a full-scale disposal site using such liners.

This project covered a 4.5-year period beginning in October 1978.

SECTION 3

LITERATURE REVIEW ON CHEMICAL LINERS USED FOR LEACHATE CONTROL*

The U.S. EPA Office of Solid Waste estimates that there are over 20,000 metal finishing facilities in the United States (1). Since wastewaters from these facilities contain acids, cyanides, hexavalent chromium, and other heavy metals, they are corrosive and can be lethal. Typical chromium-bearing and cyanide-bearing wastewaters contain up to 700 mg Cr(VI)/l, and 1,500 mg CN/l, respectively (1). These wastewater streams are generally treated separately. The chromium stream is reduced with sulfur dioxide, and the cyanide stream is oxidized with chlorine or sodium hypochlorite in an alkaline solution. The separate streams are then combined and treated with lime to adjust the pH to 7 to 9.5. The resulting sludge is approximately 85 percent (dry weight basis) metal hydroxides (2). The constituents of a typical sludge are given in Table 1.

In 1975, electroplating wastewater treatment produced approximately 24,000 metric tons of metal hydroxide sludges (2). A traditional approach to many solid waste problems has been the municipal waste sanitary landfill. A number of researchers have shown that this approach is unacceptable for metal hydroxide sludges (3-6). Leachate formed by the percolation of ground or surface water through municipal waste has a low pH and a high concentration of ammonia, organic acids and dissolved carbon dioxide. At pH conditions outside the 7.5 to 9.0 range, and in the presence of organic ligands and ammonia, the metals in the sludges form soluble metal complexes (7). Consequently, when metal hydroxide sludges are placed in a sanitary landfill environment, the metals tend to dissolve, threatening ground or surface water supplies. These sludges present a major waste disposal problem, and some form of disposal must be found which effectively immobilizes the metals or prevents contamination of water, air, and soil.

Incineration is also unacceptable since it will not destroy metals (6). Incineration volatilizes metals with low boiling points (e.g., Pb, Cd) which condense, forming small particles

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* Literature review was conducted in January 1979, and has not been updated.

TABLE 1. TYPICAL METAL HYDROXIDE SLUDGE COMPOSITION (2)

Compound	Dry Weight, %	Metal	Dry Weight, %
$Cu(OH)_2$	12.3	Cu	8.0
$Cr(OH)_3$	14.8	Cr	7.5
$Ni(OH)_3$	39.1	Ni	21.0
$Zn(OH)_2$	17.1	Zn	11.0
$Cd(OH)_2$	1.7	Cd	1.0
Impurities	15.0	Nonmetals	51.5

that cannot be effectively removed by presently available emission control devices. Other less volatile metals can be converted to sparingly soluble oxide forms in the incinerator ash (e.g., Cr, Mo). If the ash is disposed of in a sanitary landfill, some of these metals may be leached out of the ash and into water supplies.

Several relatively new technologies (e.g., chemical fixation, encapsulation, metal recovery) have been proposed for electroplating sludges, but none is sufficiently developed to be used on a wide scale. Another approach with more immediate promise is the burial of sludges in a segregated and secure landfill. Segregating the sludges from low-pH leachates which contain complexing agents avoids many of the problems cited above. Securing the disposal area involves one of several concepts:

- Locating the site in, or lining it with, clay so that leachate migration is retarded and pollutant concentrations in the leachate are attenuated.

- Lining the site with an impermeable membrane, collecting and treating any leachate.

- Surrounding the sludge with a chemical liner either to (a) ensure the alkalinity of liquids coming into contact with the sludge and of any leachates generated, or (b) to chemically retard pollutants from the leachates.

Generally, when discussing liners and liner technology, the impermeable barrier concept comes to mind. For the lifetime of the liner, an impermeable barrier is the most secure approach as it prevents any leachate movement beyond the site or any contact between ground water and the sludges. However, most impermeable liners have a limited life span, and once breached, can render a site totally insecure. Furthermore, the impermeable liner tends to create a bathtub-type effect which traps and holds leachate and must be periodically emptied. The leachate thus collected must be treated before it can be discharged (5). For more information on impermeable liners, particularly the types, characteristics, applicability to different waste streams, and associated advantages and disadvantages, refer to the work of Haxo (8).

Clay functions as a liner in several ways. Properly compacted, it can act as an essentially impermeable liner. Mixed with silt or sand, as it often occurs naturally, clay loses some of its impermeability, but can still slow the release of leachate to the point where only small quantities reach ground water at any time, effectively minimizing the pollution potential of the leachate. Clay can also function as a chemical liner, removing certain pollutants from the leachate.

Chemical liners serve several roles in waste disposal (9). Certain types of liners are used to surround the sludge with an alkaline barrier, ensuring the alkalinity of any liquids coming

into contact with the sludge. If the pH of the water or leachate is kept within a range of 7.5 to 8.8, metal solubility is kept to a minimum. Other liners react with metals in solution, causing them to precipitate or removing them through an ion exchange/adsorption process. Chemical liners do not ordinarily provide total containment. Rather, they act to reduce the rate of pollutant release to a level which will not adversely affect ground water (9, 10). To date, research on this type of liner has concentrated primarily on clay, with secondary efforts directed at limestone, hydrous iron oxides, fly ash, bottom ash, activated alumina, activated carbon, vermiculite, zeolite, and others.

The role of clay in attenuating pollutants has long been recognized, and the determination of clay content has become one of the most useful analyses of soil properties for predicting trace element mobilities in soils (11). The attenuation mechanism is not entirely understood. Sorption, ion exchange, and precipitation have been proposed as explanations. For instance, Gloyna and Sanks (12) demonstrated that the cation exchange capacity of certain soils increased with increasing percentages of montmorillonite. On the other hand, Roberts and Songrey (13) discounted the role of ion exchange because of a lack of correlation between clay content and cation exchange capacity in the soils that they studied. Rather, they attributed the attenuation potential of clay to its roles in precipitation: nucleation and particle growth. Nucleation requires the presence of minute particles, and the rate of particle growth is enhanced by large available surface areas, both characteristics of clay minerals. In either case, there is a firmly established relationship between clay content and attenuation.

Fuller and Artiola (14) demonstrated that clay removed from leachate up to nine times more Fe per gram of soil than did sands. The Fe was tightly held, and resisted any further leaching action of water. Chan et al. (15) studied a variety of materials, including illite and kaolinite clays, for their usefulness in treating metal finishing sludge leachates. Results of their lysimeter tests for the sorption capabilities of various materials are presented in Table 2. The data seem to indicate that although the sorption capability varied with the materials and contaminants tested, clay minerals were superior to the four other sorbents studied.

Griffin and Shimp (16) studied the attenuation capability of three clays (illite, kaolinite, and montmorillonite) with sanitary landfill leachate. According to their research, Pb, Cd, Cu, Cr(III), Hg, and Zn are attenuated by an exchange-adsorption mechanism in acid to neutral environments; in alkaline environments, precipitation becomes a major factor. They found that attenuation of the Cr, As, and Se anions decreased with increasing pH.

TABLE 2. SORPTION CAPACITIES OF DIFFERENT MATERIALS (15)

Contaminant	Acid Fly Ash	Basic Fly Ash	Vermiculite	Illite	Kaolinite	Activated Alumina	Activated Carbon
	ug/g†						
Calcium	123	146	1,280	1,828	930	737	283
Copper	16.5	7.5	20.5	57.5	--*	6.3	23.0
Magnesium	448	200	485	1,840	--	495	314
Nickel	4.9	2.0	3.0	7.3	--	2.5	7.2
Fluoride	0	0	0	2.7	3.6	11.4	0
COD	1,228	320	1,048	3,060	0	0	1,476

* Data not obtained.

† ug contaminant per g sorbent.

Another soil property which is useful in predicting the mobility of trace elements in soils is lime content. Lime or limestone in soil acts on trace elements in three ways: precipitation as hydroxides, precipitation as carbonates, and adsorption (17). Precipitation as hydroxides is probably the most significant, adsorption the least. Lime and limestone are commonly used in agriculture to raise the pH of acidic soils. As a liner, limestone acts to ensure an alkaline environment around the wastes, keeping them within the pH range where the trace elements are generally least soluble. Consequently, there has been considerable research into the utility of lime and limestone as liner materials.

Artiola and Fuller (18) reported that crushed limestone was more effective in retaining the cation Cr(III) than the anion Cr(VI) in municipal solid waste leachate. They concluded that the usefulness of limestone as a chemical liner will depend primarily on the pH and the volume of the solution passed through the limestone.

In other research, Fuller and Artiola (10, 14, 19) demonstrated that limestone significantly slowed the movement of Be, Cd, Cr(III), Fe, Ni, and Zn. Results of some of their column studies with limestone are presented in Table 3. The attenuation reactions were dependent on contact time, pollutant concentrations, and leachate pH. They also found that layering or lining the soil with limestone was more effective than mixing lime or limestone into the soil. Such a mix can set up as a soil cement, producing an impervious barrier. Acid leachate can eat through this soil cement, forming cracks and fissures through which leachate can flow without reacting with the lime.

The potential of limestone as a liner has led to its employment at several waste disposal sites, despite the uncertainties still inherent in its use. Lancy (6) reported a test program in Kentucky utilizing a 4-in. limestone gravel base to contain 10 to 15 percent solids metal hydroxide sludges. These tests showed significant reductions in leachate concentrations of Cr(III), Zn, and Ni. Concentrations of CN and Cr(VI) in the sludge leachate were too low to draw any conclusions concerning their attenuation.

Crumpler (11, 12) reported on the use of limestone by the Armstrong Cork Company carpet plant near Lancaster, Pennsylvania. This plant produces a heavy metal sludge mixed with rubber latex which is deposited in a trench lined with a minimum of 3 inches of limestone. The system has been in operation since 1971 with no apparent effect on ground water.

Other soil properties which are useful in predicting the mobility of trace elements in soil are the levels of hydrous oxides of Fe and, to a lesser extent, Mn. Hydrous iron oxides act as scavengers, removing trace elements by a process of sorption and fixation. The extent and rate of reversibility of this

TABLE 3. LIMESTONE ADSORPTION CAPACITIES (19)

Element	Test Solution Concentration (mg/l)	Adsorption After 48 Hours (ug/g)	Supernatant Concentration (mg/l)
Nickel	110	210	89
Zinc	110	280	82
Chromium	26	260	ND*
Chromium	85	380	48
Cadmium	86	770	9
Arsenic	43	61	36
Arsenic	103	133	90
Beryllium	103	590	35
Mercury	100	794	21
Selenium	35	298	5
Selenium	96	725	23
Vanadium	110	325	75
Copper	540	5,360	5
Copper	1,032	10,126	6
Copper	1,385	13,772	7
Aluminum	850	8,500	ND
Lead	865	8,630	2

* None detected.

removal reaction are not well understood. It is known, however, that soils rich in hydrous iron oxides act as sinks for heavy metals (17, 19).

Chromium(VI) moves much more rapidly in soils than does Cr(III) (17). It has been demonstrated that Cr(III) migration was retarded by hydrous iron oxides (19). Thus, hydrous iron oxides could be used to control Cr(VI) by converting it to the less mobile trivalent form (10):

$$Cr_2O_7^{-2} + 14\ H^+ + 6\ Fe^{+2} \longrightarrow 2\ Cr^{+3} + 6\ Fe^{+3} + 7H_2O$$

In practice, soils rich in hydrous ferrous oxide can be produced by applying ferrous sulfate solutions to the soil. The sulfates change rapidly to the hydrous oxide form, coating the soil particles with very thin hydrous oxide layers. A problem with this approach is that, if conversion to the oxide form is incomplete, iron may leach into and contaminate underlying ground waters. Another problem is the possibility that a reducing environment could form in the region of the layer, releasing soluble ferrous iron and any trace elements sorbed onto the layer (13).

Among the artificial materials that have been proposed as disposal site liners are fly ash, activated carbon, and activated alumina. Fly ash is the most researched of these three. Fly ash is attractive, because it is a waste product of coal and oil combustion, and because it employs several attenuation mechanisms common to soil systems. Fly ash is a fine particulate material composed of an alumino-silicate matrix incorporating oxides of various trace elements. It is generally alkaline because of the presence of alkali and alkaline earth oxides. Fly ash attenuates trace elements through a combination of precipitation (due to the high pH), surface adsorption, and chemical incorporation into the alumino-silicate matrix.

Gangoli et al. (20) used fly ash to treat water in laboratory studies. Experiments with 10, 25, 50, and 100 ppm solutions of Al, Cr(III), Mn, Fe, Ni, Cu, Zn, Sr, Cd, and Pb indicated essentially complete removal of Al, Cr, Mn, Fe, Ni, Cu, and Cd. Interestingly, aqueous extracts of the fly ash could be used to effectively treat 10 ppm solutions of these metals, demonstrating the precipitation effect due to the alkalinity of the fly ash. Gangoli et al. theorized that there was also some adsorption of cations on the silica surface through ligand exchange-type reactions. They further estimated that there could be partial removal of $Cr_2O_7^{-2}$ due to chemisorption associated with bonding between active alumina sites and CrO_4^{-2}.

Chan et al. (4, 15) have done considerable research on the treatment of leachate with fly ash beds. Partial results of their research are shown on Table 2. Gaasch and Law (21) demonstrated that fly ash has a cation exchange capacity of 1.8 to 3 meq/100 g.

There are several potential problems associated with the use of fly ash as a liner material. There is still some uncertainty over the safety of land disposal of fly ash because of its heavy metal content. Ground water contamination, due to leaching from the ash itself, is a distinct possibility. However, the high pH associated with basic fly ash and the metal hydroxide sludges generally keeps these materials immobile (22). Another problem is the potential for cementation due to the lime content of the fly ash. Under the right conditions, the fly ash can set up like a soil cement with the associated problems discussed earlier.

Chan et al. (15) also studied the use of activated carbon and activated alumina for removing metals from leachate. In general, activated alumina is effective in removing Ca, Mg, and fluoride, largely through a process of ligand bonding. Activated carbon can effectively remove Cu, Ni, and organics. Both are relatively expensive, and neither is as effective as the other liner materials discussed above.

Natural zeolites, being an ion exchange material, have also been tested for their ability as liner material (4). The results have not been favorable; removal efficiencies have been much lower than expected and generally lower than the other materials studied.

Flue gas desulfurization (FGD) sludges have also been considered as liner material because of their high lime/limestone content and their relatively low material cost. In general, though, these sludges are difficult to dewater, and consequently are expensive to transport and install.

An interesting outcome of the research of Chan et al. has been the idea that a layered liner may provide the best protection (4, 15). This approach takes advantage of the attenuation capabilities of each layer while overcoming the liabilities of any one material. While beyond the scope of this present study, the layered liner system is an approach that merits consideration for future research.

RECOMMENDED CHEMICAL LINERS

Based on the chemical nature of the sludges and leachates, and on demonstrated attenuation mechanisms, it can reasonably be expected that soils or liner materials which are strongly alkaline and contain large quantities of lime, hydrous iron or aluminum oxide, or clay would exhibit strong attenuating capabilities. All of the liner materials mentioned earlier possess one or more of these characteristics. However, no single material is effective in removing all the chemical contaminants from the sludge leachate and, according to Chan et al. (15) two, three, or four different liners could be collectively combined to reduce sludge leachate contaminant levels.

Limestone is commonly used in agriculture to raise the pH of acidic soils. As a sludge liner, it could retard the formation of acid leachate, neutralize any which was formed, and, through precipitation, prevent the mobilization of cationic metal species that are present in the sludge or leachate (11). The potential attractiveness of limestone as a liner material has led to its use as such at several sludge disposal sites without adequate justification from field research, although some laboratory testing has been conducted (5, 6). Consequently, because of immediacy of the need, limestone was recommended for testing in this study.

The role of hydrous iron oxides as a heavy metal scavenger in soils and water has long been recognized (23, 24). Laboratory studies on soils amended with ferrous sulfate and on soils naturally high in iron oxides have demonstrated a high capacity for retaining trace elements (11, 19). If iron oxides could be proven to be an effective liner in field trials, they would provide a relatively widespread and inexpensive liner option. The combination of proven effectiveness in water and laboratory trials, plus their availability, ease of application, and low cost make iron oxides an extremely attractive option. They were, therefore, the second liner material recommended for this study.

Basic fly ash is a waste product of coal combustion and is readily available anywhere coal is used for energy production. Although its chemical content varies, fly ash is generally an iron aluminum silicate with additional lime, magnesia, alumina, iron oxide, and trace quantities of several other elements (25). Fly ash thus possesses most of the characteristics necessary for attenuating heavy metals. When compacted and hardened, fly ash resembles clay in its low permeability. It contains lime and iron oxides which are effective in retaining trace metals. Because of its high oxide content, fly ash tends to be basic, which favors attenuation of most heavy metals.

Basic fly ash has not been extensively studied as an attenuating liner material, despite its potential. Consequently, because of its theoretical usefulness, its availability and low cost, and the absence of any significant research, basic fly ash was the third material recommended for evaluation in this study.

This recommendation was not intended to suggest that the remaining liner materials were inappropriate, although some may be. They were rejected as proposed liners in this study for a variety of reasons. Clays have long been proven to be effective, both as impermeable liners (when tightly packed) and as attenuating liners (in clay/sand mixtures). They have been tested against virtually every type of waste and leachate. Several clay minerals have recently been studied extensively as liners for metal hydroxide sludges and the optimum conditions for their use have been identified (15). Clays were excluded from this study, because further testing would have been redundant. In light of the state of the knowledge about and potential of the materials that

were recommended, clays are well researched and well characterized.

In comparison with the materials discussed above, the other materials mentioned earlier appear either to be less useful as attenuating liners or have applicant/cost factors which are not favorable. FGD sludges can be difficult and expensive to transport due to their dewatering characteristics. Thus, despite their high limestone/lime content and relatively inexpensive material cost, FGD sludges were deemed inappropriate. However, when treated or stabilized (e.g., by mixing with appropriate amounts of fly ash), the sludges can be hardened (to a permeability coefficient of 10^{-7} to 10^{-8} cm/sec), greatly enhancing their potential for use as a landfill liner.

Activated carbon and activated alumina were shown to have good contaminant removal and retention characteristics, but not as good as those of some other liner materials studied (clay, for example) (15). In addition, they can be considerably more expensive than the other liner materials recommended for inclusion in this study. Natural zeolites have not proven in laboratory testing to be particularly effective (15). They are essentially ion exchange materials that work best on divalent cations. Consequently, anions or other cations may pass through. The high sodium content of many metal hydroxide sludges may tend to regenerate the zeolites, freeing any cations which are retained. Thus, zeolites were also rejected for this study.

The three liner materials chosen for this study represent three different types of liner. They are relatively inexpensive in both materials and application. They have a high potential, but are unproven in the particular application in question. In the case of limestone, its increasing application at waste disposal sites in advance of controlled trials virtually demands immediate study.

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SECTION 4

MATERIALS AND METHODS

STUDY SITE

The study site was situated within the NW quadrant of SCA Services, Inc., a secure landfill located near Rimini, in Sumter County, South Carolina. The secure landfill is situated in an open-pit opal claystone mining operation.

The area generally has a mild, humid climate; average normal temperatures range from the low 90's in the summer to the 30's in the winter months. Average annual precipitation is just under 119 cm (47 in.) and is fairly evenly distributed throughout the year, but heavier in summer and lighter in the fall. Average annual potential evapotranspiration ranges from 91 to 99 cm (36 to 39 in.).

Data available at SCA Services, Inc., show the occurrence of two water-bearing zones: a shallow water table aquifer contained within the overburden and the confined Tuscaloosa formation aquifer which lies below the Black Mingo formation (Figure 1). Mining of the opal claystone within the Black Mingo formation required the complete removal of the overburden, leaving only one water-bearing unit, the confined Tuscaloosa aquifer, lying beneath the claystone.

CELL DESIGN

Several initial designs were proposed by EPA/OSW with variation mainly in the side slopes. Because both the size of the study site and the sludge quantity were limited, a box-type design was finally selected by OSW (Figure 2). Special features of the test cell were:

- Dimensions - The cell was a box 2.4 m (8 ft) square and 1.8 m (6 ft) deep.

- Contingency Plan - A polymeric membrane (20-mil PVC) lined the entire bottom surface and sides of each test cell. It was intended to contain any leachate that might pass through the chemical liner. A layer of bank sand (subgrade) lay beneath the PVC liner to provide both membrane protection and the proper slope drainage to the collection point. The selection of PVC was based on the

PERIOD	EPOCH	FORMATION	COLUMNAR SECTION	THICKNESS IN METERS	CHARACTER
QUATERNARY	RECENT	ALLUVIAL DEPOSITS		0-3	SAND, SILT, CLAY
		UNCONFORMABLE			
	PLEISTOCENE	RED CLAYEY SAND		0-3.4	RED CLAYEY SAND
		UNCONFORMABLE			
		UNDIFFERENTIATED ALLUVIAL DEPOSITS		0-	PREDOMINANTLY RED, TAN, AND WHITE C.F. SANDS; SILTY TO CLEAN, LITTLE FINE GRAVEL
		UNCONFORMABLE			
		VARIEGATED CLAY		0-2.6	LAMINATED SILTY CLAY TO CLAYEY SILT; TRANSITION ZONE AT BASE
		UNCONFORMABLE			
TERTIARY	EOCENE	B M FORMATION: BUHRSTONE UNIT		0-0.6	WHITE BUHRSTONE
		CONFORMABLE?			
		RED SAND UNIT		0-4.6	ORANGE-RED M.F. SAND (OFTEN CROSS-BEDDED) TO CLAYEY SILT
		CONFORMABLE?			
		OPAL CLAYSTONE UNIT		0-21.3	BLACK, GREY TO WHITE OPAL CLAYSTONE; THIN TO THICK BEDDED; OCC. SILTY, IMPURE OR SANDY BEDS; JOINTED, TYPICALLY CAPPED WITH VENEER OF RESIDUAL CLAYS; WEATHERS TO A BROWN OR LIGHT GREY, DRYS UPON EXPLOSURE TO THE AIR
		CONFORMABLE?			
		BASAL CLAY UNIT		0-4.6	BLACK UNCTUOUS CLAY; THIN-BEDDED, SEMICONSOLIDATED, JOINTED, BASAL SANDSTONE AT CONTACT
		UNCONFORMABLE			
CRETACEOUS	UPPER CRETACEOUS	T FORMATION		61+	INTERBEDDED BLUE-WHITE CLAYEY SANDS, GREY SANDS, AND PURPLE-GREY CLAYS; HIGHLY MICACEOUS, SOME ARKOSIC ZONES, UNCONSOLIDATED

Figure 1. Geologic column of formations encountered beneath study site.

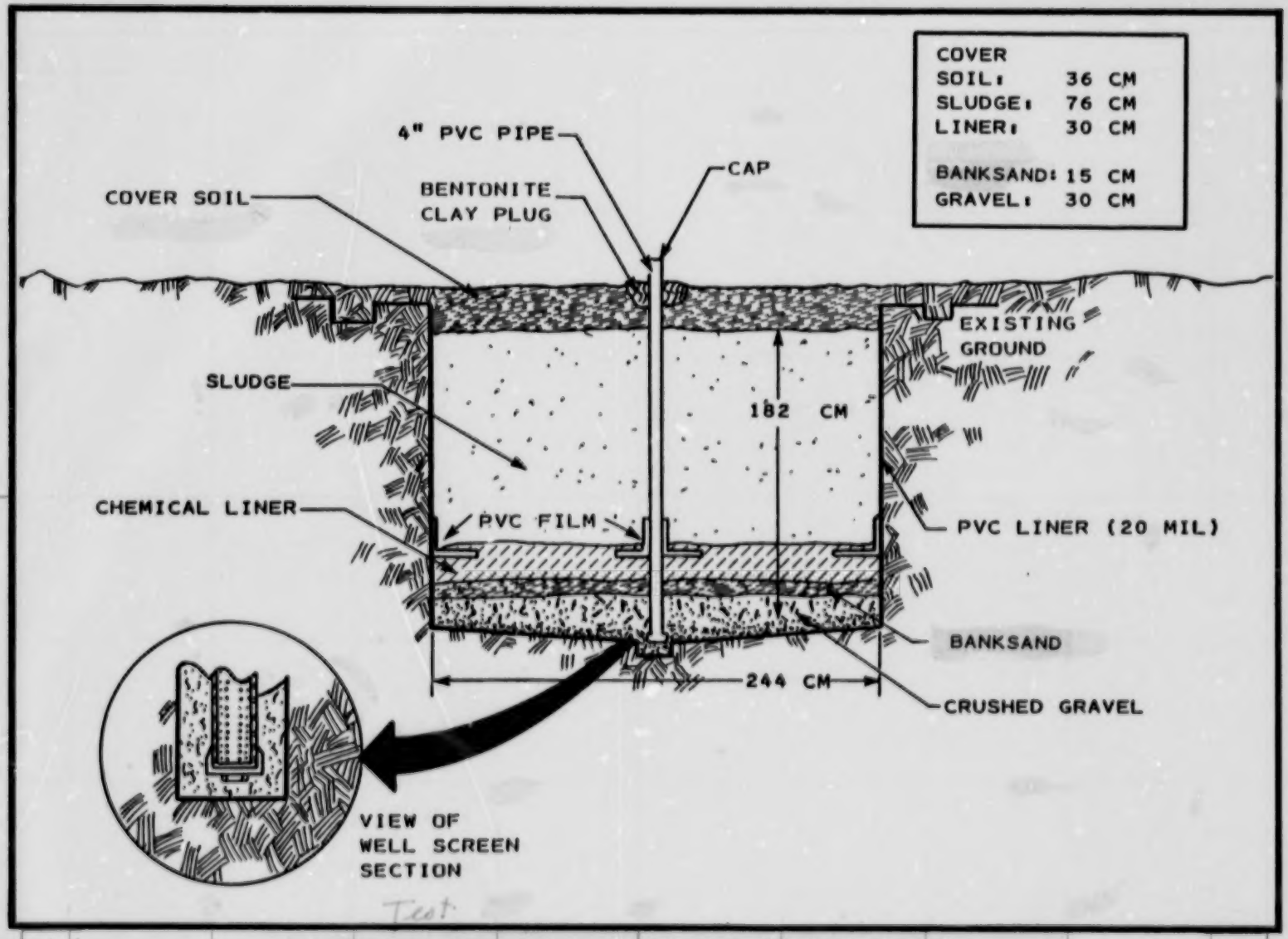

Figure 2. Test cell design (Not To Scale).

low material cost, flexible form, and short duration (<5 yr) of this study. Compatibility of the PVC liner with sludge leachate was not determined prior to selection.

- Crushed gravel layer (approx. 30 cm) - This layer was intended to support the chemical liner and facilitate the vertical flow of leachate towards the collection device.

- Bank sand layer (approx. 15 cm) - This layer, sandwiched between the gravel layer and chemical liner, was designed to prevent the migration of chemical liner particles through gravel into the leachate collection device.

- Chemical liner layer (approx. 30 cm) - The thickness of this layer was selected to allow the liner to "filter" the leachate as it passed through, while retaining the heavy metals or other hazardous constituents. A thinner layer (<15 cm) might have resulted in uneven distribution of the chemical liner; continuous cracks or holes might have formed, allowing direct passage of the leachate. A thicker layer (>30 cm) might have reduced leachate passage toward the collection device.

- Sludge layer (approx. 76 cm) - The quantity (thickness) was arbitrarily determined, but was partially based on the content and solubility of the heavy metals of concern such that the sludge would not be depleted of these metals by leaching under the experimental conditions.

- Cover soil layer (approx. 36 cm) - Surface soil from the area was used as a cover, simulating actual landfill conditions.

- Leachate collection system - The system consisted of a 10-cm (4-in.) diameter perforated PVC pipe extending into the bottom of the gravel layer. Leachate that had accumulated in the gravel layer was drawn through a screened portion of the pipe.

Due to budgetary and resource constraints, only seven test cells were constructed. Fly ash, agricultural limestone, and hydrous oxides of iron were each used to line two test cells; the single control cell used bank sand in place of a chemical liner.

CELL CONSTRUCTION

Construction was started on the seven cells in July 1979. The area, measuring 49 m x 17 m (148 ft x 52 ft), was cleared of vegetation, and a road leading to the cells was graded. After the area was surveyed, the cover soil was removed, and a table (flat area) was cut into the claystone. One side of a hill next to the table was cut to make room for maneuvering field equipment.

The cells were laid out according to the design in Figure 2. They were constructed by excavating square holes into the claystone with a backhoe. The bottom of the cell was backfilled with 30 cm (12 in.) of bank sand (available on site) and contoured to a 1 on 12 slope with a 15-cm (6-in.) deep sump in the center. This facilitated leachate collection and served to support and protect the PVC liner from puncture.

The PVC liner was placed and folded into each of the cells, with a lip of the liner placed in a 30-cm (12-in.) trench which encircled each cell. A 10-cm (4-in.) PVC pipe with a cap and fabricated well screened bottom was placed in the center of the cell into the sump and secured with guy wires. A 30-cm (12-in.) layer of crushed and washed gravel was then placed on top of the PVC liner. Bank sand (15 cm [6 in.]) was placed on top of the gravel and a 30-cm (12-in.) layer of chemical liner was placed over the bank sand. A rectangular 30-cm (12-in.) yoke was pulled down over the PVC pipe and cemented around it. The lower portion of the yoke was buried approximately 5 cm (2 in.) in the chemical liner to prevent short-circuiting of leachate along the pipe. The liner was tamped to assure uniform compaction, and the sludge was introduced into the cell and spread to a depth of 76 cm (30 in.) on top of the chemical liner. Dikes were built around the edges of the cells to keep rainwater from running either on or off the surfaces of the cells.

Due to the considerable delay in cell construction and availability of the quantity of sludge needed, two sources of sludge were used in this study; Crescent Tool Company at 17 percent solids (a flowable yellow-green to green mud of fine consistency); and kiln dried sludge from the Wolverine Brass Company (dark blue). Various quantities of Crescent Tool sludge were initially placed into each cell. This was followed by successive and sometimes alternating layers of Wolverine, Crescent, Wolverine sludge, etc., until each cell was filled with approximately equal amounts of both sludges. All cells, however, were not filled (after the initial charge of Crescent sludges) in the same manner. Some may have had only two layers; others had 3 or more. For example, Cell #1 (control), was filled with 2 initial additions of Crescent sludge followed by 2 successive additions of Wolverine sludge, totaling about 10,400 kg of total sludge addition. Cell #2, on the other hand, was initially charged with Crescent sludge followed by Wolverine, Crescent, Wolverine, and perhaps more Crescent. Each of the cells contained approximately the same total weight of sludge. The large size of the cells prevented any type of mechanical mixing other than hand raking.

The cell construction plan called for adding 208 liters (55 gal) of water, equivalent to 3.5 cm (1.38 in.) of rainfall, to each cell after the sludge had been deposited in the cells. This water was not needed, however, as summer storms soaked the area during and after construction. These heavy rains may partly have been responsible for some of the anomalies observed when cores were withdrawn from each cell.

The cells were allowed to equilibrate for a few days and were then filled with top soil from the area. The top of the pipe was packed with a clay plug to preclude short circuiting down the pipe. The area over each cell was leveled and diked to promote uniform percolation through the cell area.

Water that accumulated in the sump during construction was pumped almost daily. Although all cells were pumped dry during this time, it was evident that some leaching had occurred prior to the onset of the monitoring program.

CHARACTERIZATION OF RAW MATERIALS

Soils and Sand

Selected characteristics of the soils are given in Table 4. The surface soil served as cover soil in cell construction. Subsurface soil is typically opal claystone material that lies beneath the test cells. Both soil types are acidic but exhibit marked differences in organic carbon content, cation-exchange capacity (CEC), and texture. The bank sand was not analyzed.

TABLE 4. SELECTED CHARACTERISTICS OF SOILS

Sample	pH	Organic C (%)	CEC (meq/100g)	Particle Size Distribution (%)			Texture
				Sand	Silt	Clay	
Surface Soil	5.0	0.35	12	70.4	16.6	13.0	Sandy Loam
Subsoil	4.8	0.03	35	24.9	25.5	49.6	Clay

Chemical Liner Materials

Fly ash was obtained from the South Carolina Electric & Gas Company (Lake Murray coal-fired plant), Lexington, South Carolina in July 1979. It had a pH of 6.8 and contained 2.49 percent Al, 0.01 percent Fe, 0.46 percent Ca, 100 ppm Mn, 270 ppm B, 22.6 ppm As, and 1.4 ppm Se. The hydrous oxides of iron were prepared by mixing an oven-dry reagent-grade ferric sulfate with sand at 5 percent of the mixture, resulting in a mixture with pH of 6.3 and total Fe of 0.17 percent. Agricultural limestone was purchased from a local distributor. Eighty-one percent of the limestone particles passed U.S. Sieve No. 8 (0.0937 in.).

Approximate chemical characteristics of the two metal hydroxide sludges used are given in Table 5. Both the Wolverine Brass Company and Crescent Tool Company sludges were alkaline (pH

TABLE 5. APPROXIMATE CHEMICAL CHARACTERISTICS OF SLUDGES USED*

Parameter	Wolverine Brass	Crescent Tool
pH (1:1)	8.8	8.8 - 9.1
	(%)	
Cr (Total)	2.7	7.0
Fe	0.7	4.8
Ni	1.2	6.0
Zn	1.6	0.5
Pb	0.2	0.05
Cu	2.1	1.4
B	0.1	-
	(mg/kg)	
Mn	56	650
Hg	-	1
Cd	23	7
Se	4	-

* Oven-dry weight basis.

8.8 to 9.1). The Crescent Tool sludge contained more Cr, Fe, and Ni than the Wolverine Brass sludge.

LEACHATE MONITORING

Leachate Collection

Leachate samples were taken from all cells on or about the 15th of each month for approximately the first year and a half. After that, an attempt was made to coordinate sampling time with fixed rainfall levels. Prior to the first sampling in December 1979, the cells were pumped dry. Samples were drawn from the bottom of the gravel layer through a plastic hose inserted into the PVC pipe. Each leachate sample was collected in a container which had been purged and was continuously purged with CO_2 during sampling (1). The sample was then transferred to two air-tight sample containers, one of which contained nitric acid for metal analysis. All leachate samples were refrigerated (4°C) during transport to the laboratory; analyses were generally performed within 48 hours.

After sampling was completed, each cell was pumped dry. This assured that leachate sampled each month represented the liquid percolating through the sludge and liner material during that period.

To compare the amount of leachate generated among the seven cells, leachate depth and volume in each cell were measured during the second year of sampling. Rainfall was recorded off-site until December, 1981. Thereafter, on-site recordings were made.

LEACHATE ANALYSIS

Each leachate sample was analyzed for pH, electrical conductivity (EC), Cr(VI), Cr(III), Cd, Cu, Fe, Mn, Ni, Pb, and Zn. The samples were also analyzed selectively for Se, CN, B, and Hg. The analytical methods used were those of Standard Methods (2), and are summarized in Table 6.

CORE SAMPLING AND ANALYSIS

After the last set of leachate samples was collected (mid-August 1982), core samples were taken through the different layers in the cells to assess the vertical distribution of selected metals. Core sampling was performed first by removing the top soil layer (until sludge layer was visible) and then slowly driving a 1.7-m (5-ft) long, 4-in. stainless steel shelby tubes into the cell. The pipe was driven about 15 cm (6 in.) into the claystone beneath the cell; the clay served as a plug to prevent the materials in the pipe from falling out as the tube was withdrawn. If the plugging procedure failed to work, the core sampling was repeated. Each pipe was sealed with paraffin to prevent moisture loss.

TABLE 6. ANALYTICAL METHODS USED FOR LEACHATES

Parameter	Procedure*
pH	Glass Electrode
EC	Conductivity Meter
CN	Colorimetry
B	Carmine Method
As, Se	Gaseous Hydride Method
Hg	Cold Vapor/Flameless Atomic Absorption
Cr(VI)	Colorimetry (Reaction with Diphenylcarbazide in Acid Solution)
Cr(III)	Total Cr-Cr(VI)
Cr, Cd, Cu, Fe Mn, Ni, Pb, Zn	Atomic Absorption

* Standard Methods for the Examination of Water and Wastewater, 15th ed. (2).

The pipes were opened vertically and the different layers were sectioned; samples were placed in glass jars for subsequent chemical analyses. The various layers were considerably compacted by the driving force applied during coring.

The samples were air-dried and pulverized (except gravel). The soil, chemical liners, and sludge samples were digested in aqua regia (0.5 ml conc. HNO_3 and 5 ml conc. HCl) for total metal analysis. (For Cr(VI), the samples were extracted with 0.1 M KH_2PO_4.) For gravel, a 0.5 N HCl extraction was used. Methods of analysis were the same as those used for leachate samples (Table 6). EPA quality control standards for trace metals were included in all analyses.

SITE CLEANUP

After the core samples had been taken, the materials in the cells were excavated and hauled to the SCA landfill for disposal. The side walls and bottoms of the cells were further scraped to remove any residues that were left behind. The voids were filled with powdered claystone available on site. Future use of this site was not known at the time of cell closure.

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SECTION 5

RESULTS AND DISCUSSION

The data on leachate volume, pH, electrical conductivity, and metal concentrations are shown in Figures 3 through 13. In each case, the test cell values are averages of the values obtained from the duplicate cells (only one control cell was constructed). In many cases, the first two samples have been omitted from the analysis; the values were erratic and may have been artifacts of the construction process.

LEACHATE VOLUME

When this study was initiated, the volume of leachate generated from the test cells was not considered relevant to the evaluation of liner performance. In fact, a porous chemical liner was preferred so long as it retained heavy metals in the leachate. A bathtub condition was to be avoided.

As the leachate monitoring progressed, it became evident that the mass balance data would be desirable to better understand the leaching rate. These data, coupled with metal analysis of the sludge and liners at the end of the study, could be useful in the evaluation of the metal retention capacity of the liners tested. Thus, leachate volume was measured in the second year of the monitoring program. The data are shown in Figure 3. Rainfall data is also superimposed onto this figure.

The volume of leachate generated in the control, limestone, and iron oxide cells fluctuated greatly over sampling time. There appeared to be little or no correlation between precipitation and the volume of leachate pumped from the test cells. Rather, the differences in leachate generation were due principally to the differences in the permeability of the limestone and fly ash liners. Overall, the limestone cells generated the largest volumes and showed the greatest fluctuation; fly ash cells yielded the lowest volumes and least variations.

Although an effort was made to pump out the leachate completely (by pumping until the pump lost suction and no more leachate was obtained), there was evidence to indicate that the leachate pumping technique did not perform satisfactorily. More leachate could have been obtained from some of the test cells if additional drain time had been allowed; consequently the volume data was considered questionable. During later sampling periods, both the initial volume of leachate pumped and the total volume

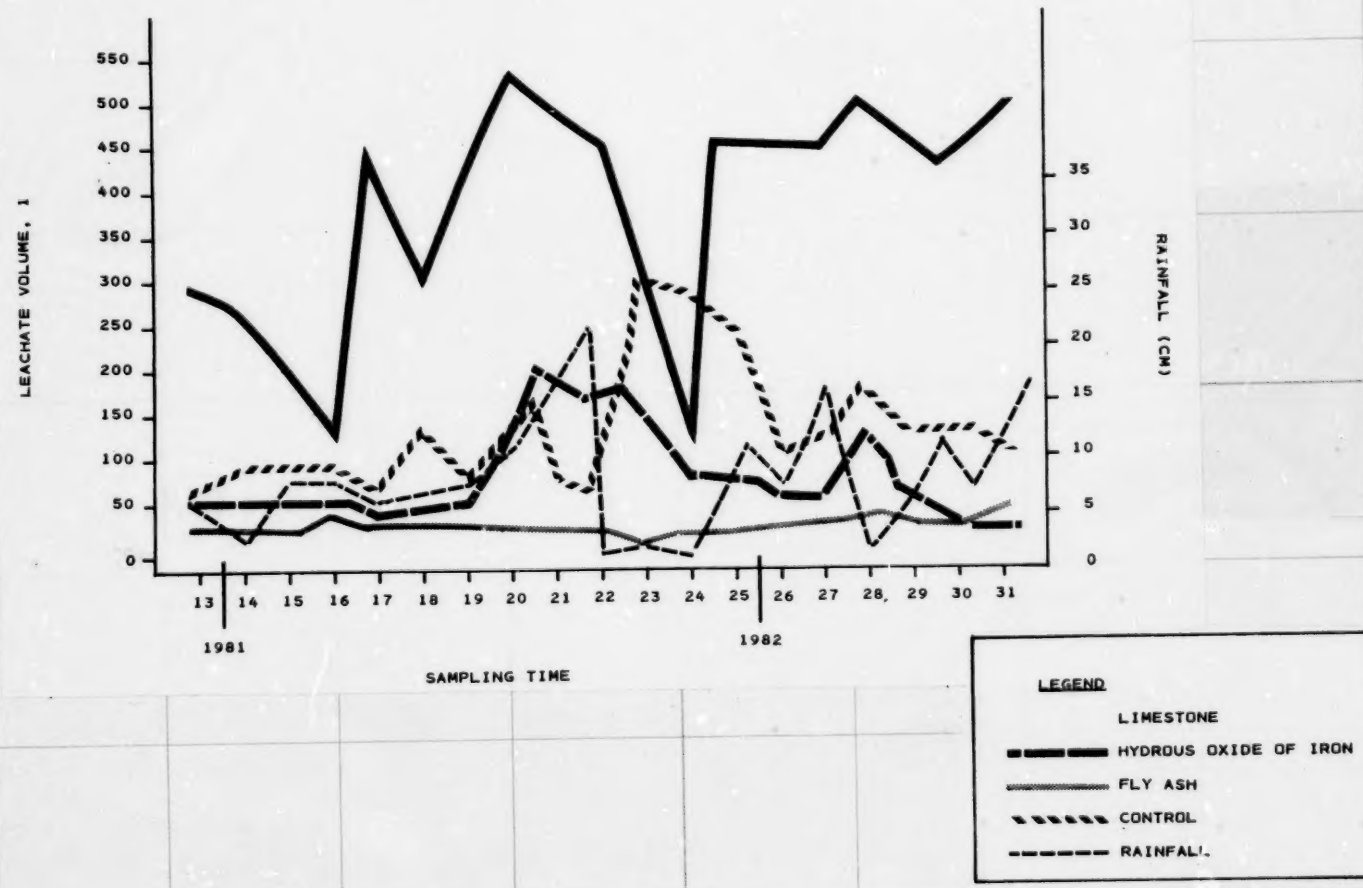

Figure 3 . Leachate volumes vs. sampling time.

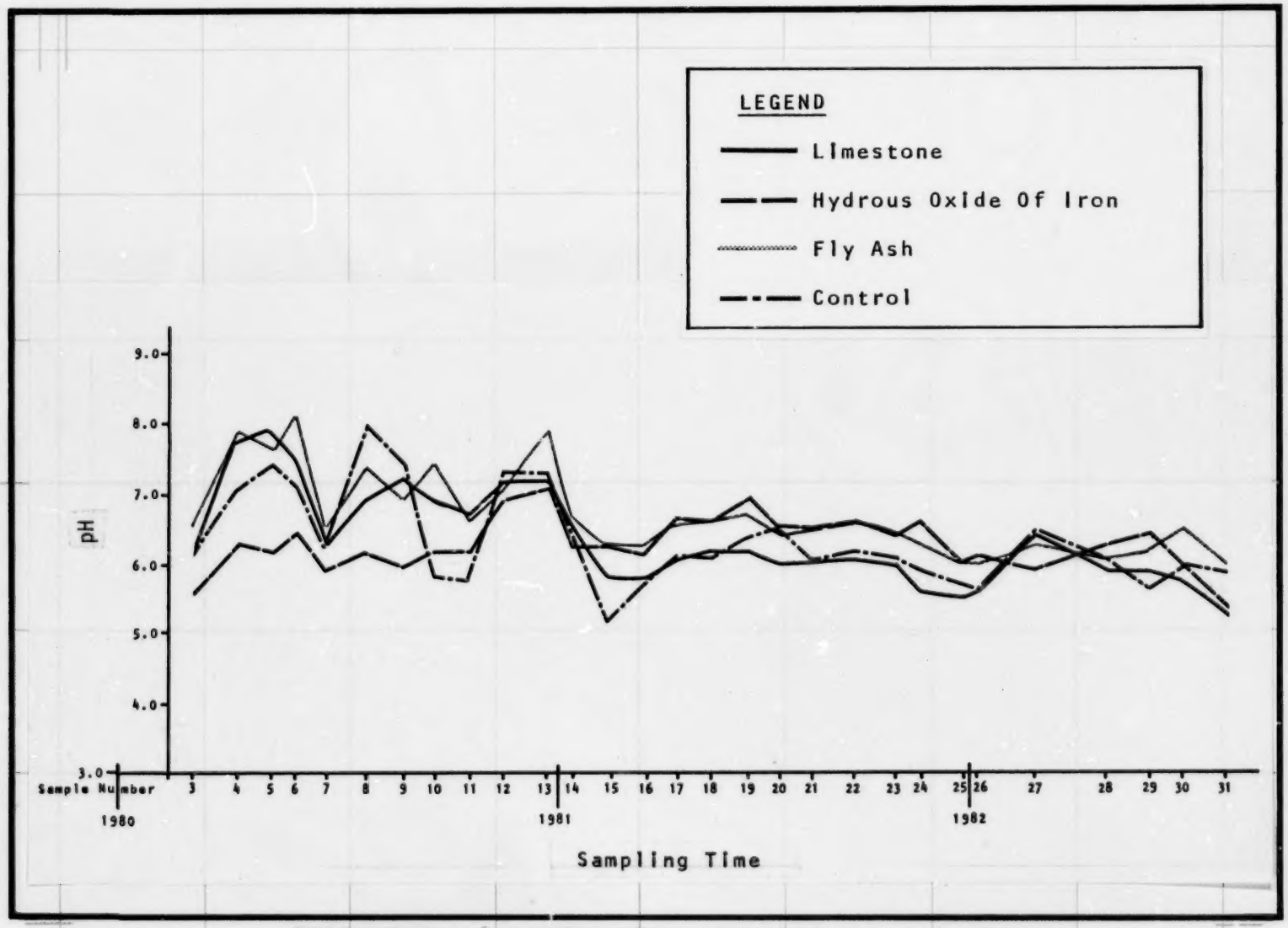

Figure 4 . Leachate pH vs. sampling time.

5-2

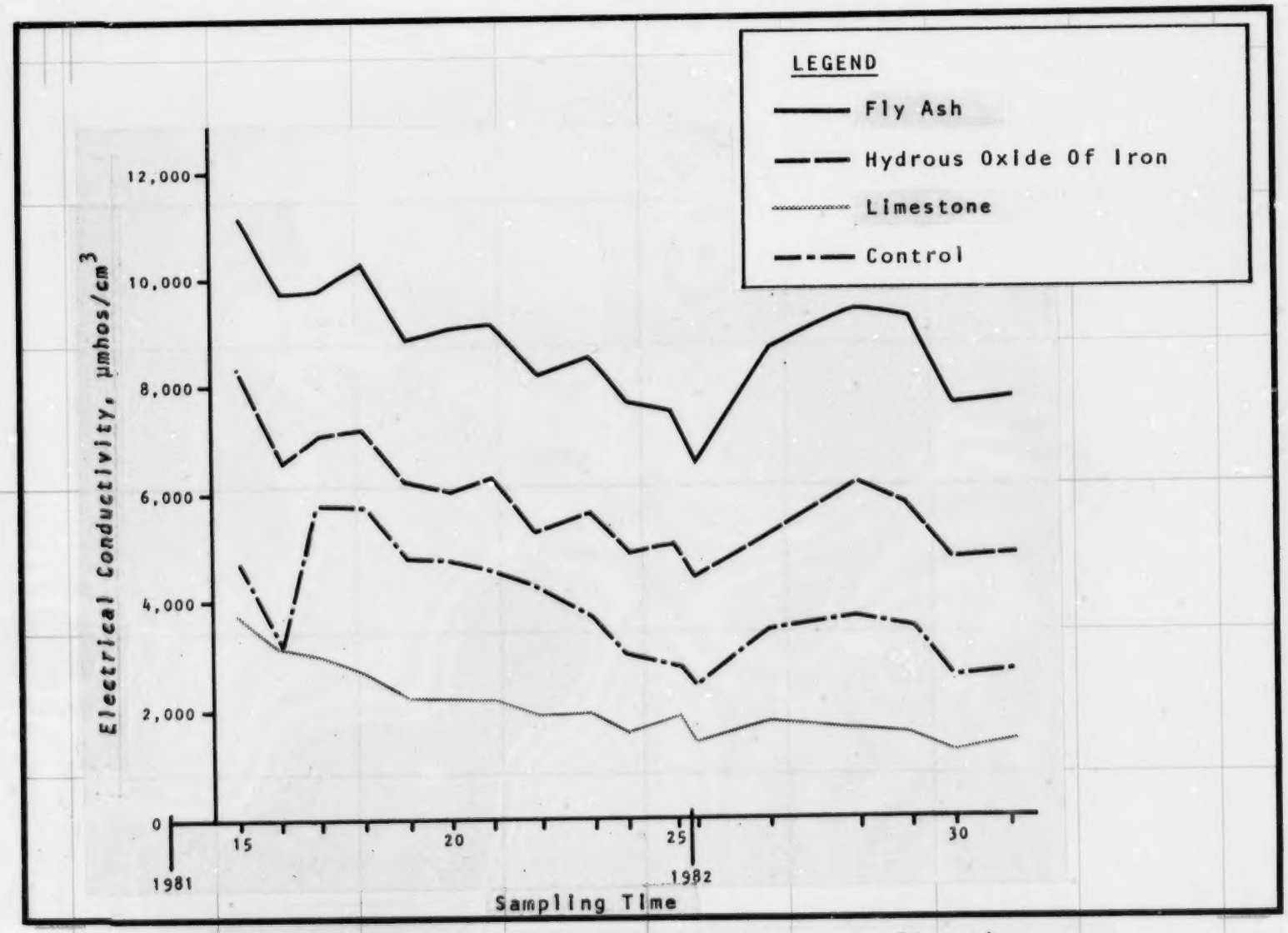

Figure 5 . Electrical conductivity vs. sampling time.

5-3

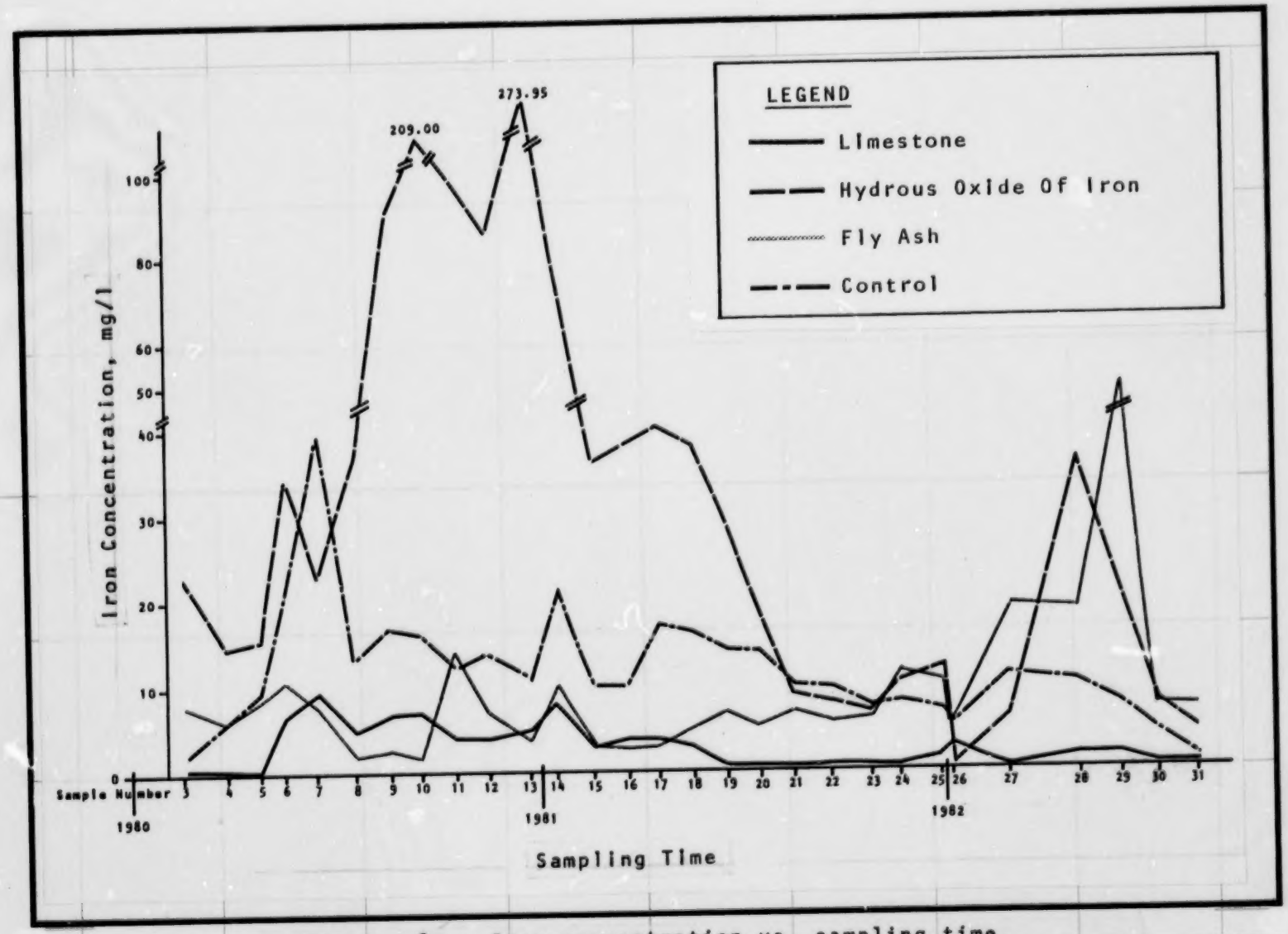

Figure 6 . Iron concentration vs. sampling time.

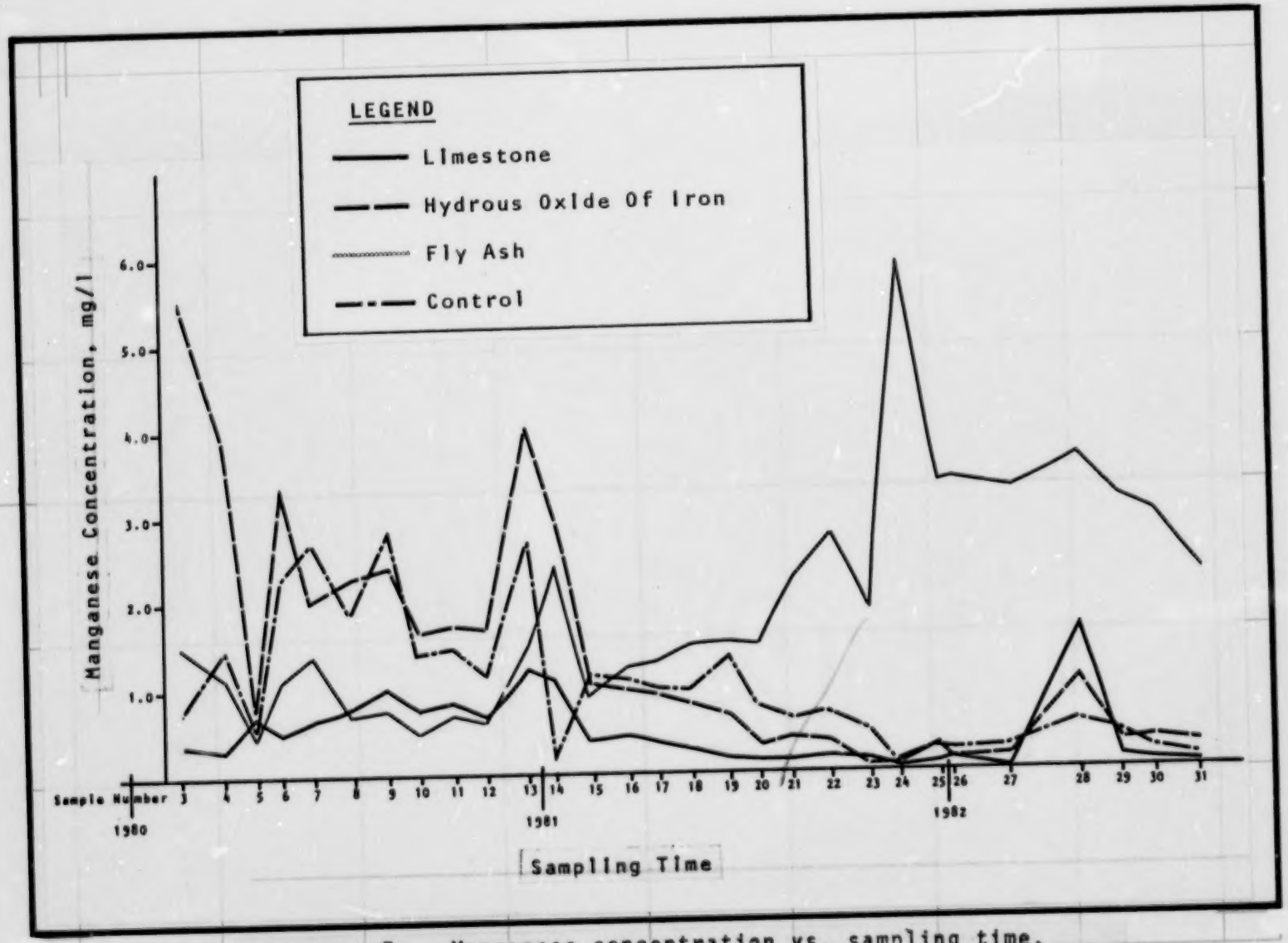

Figure 7 . Manganese concentration vs. sampling time.

5-5

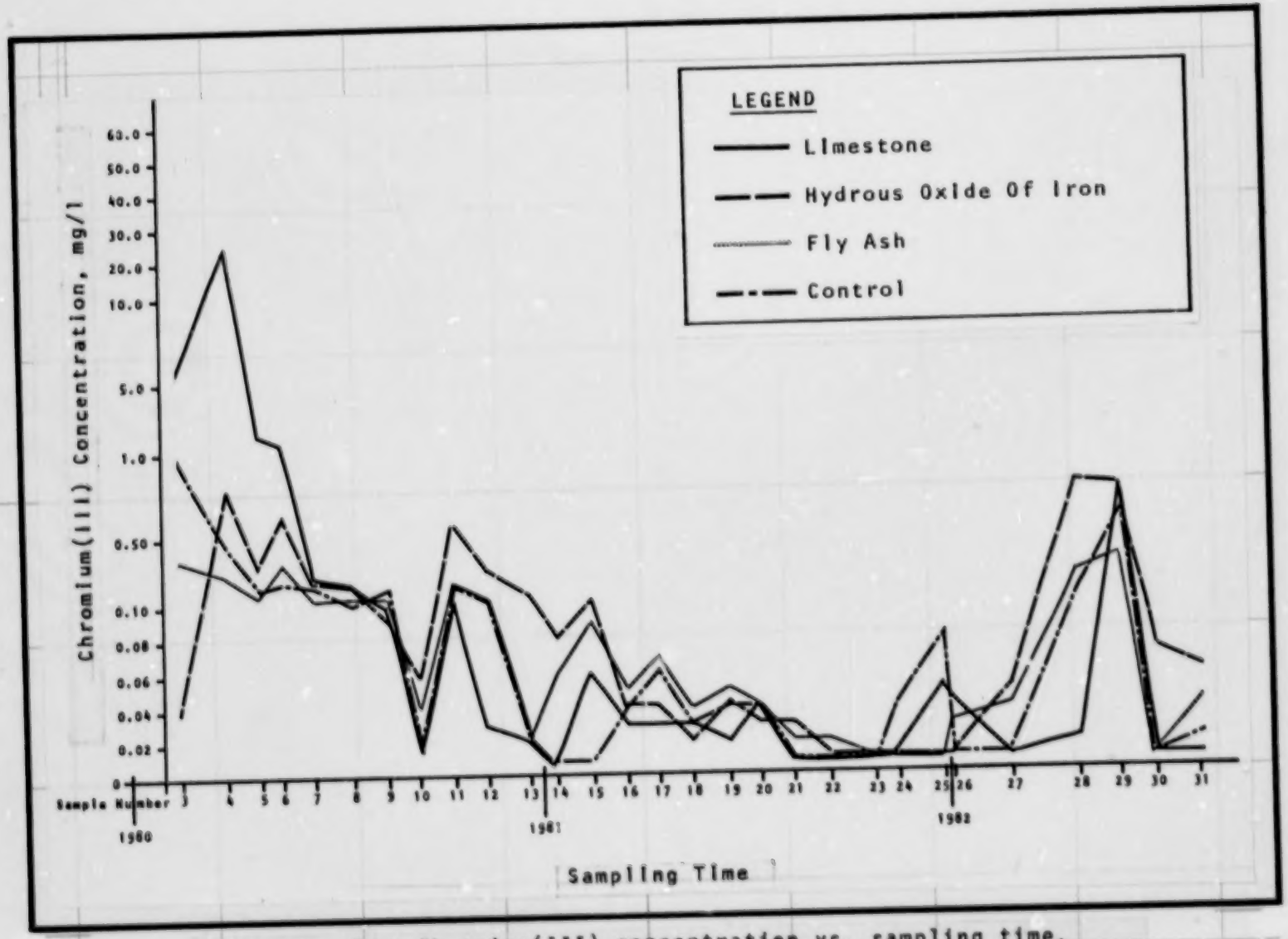

Figure 8. Chromium(III) concentration vs. sampling time.

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5-40

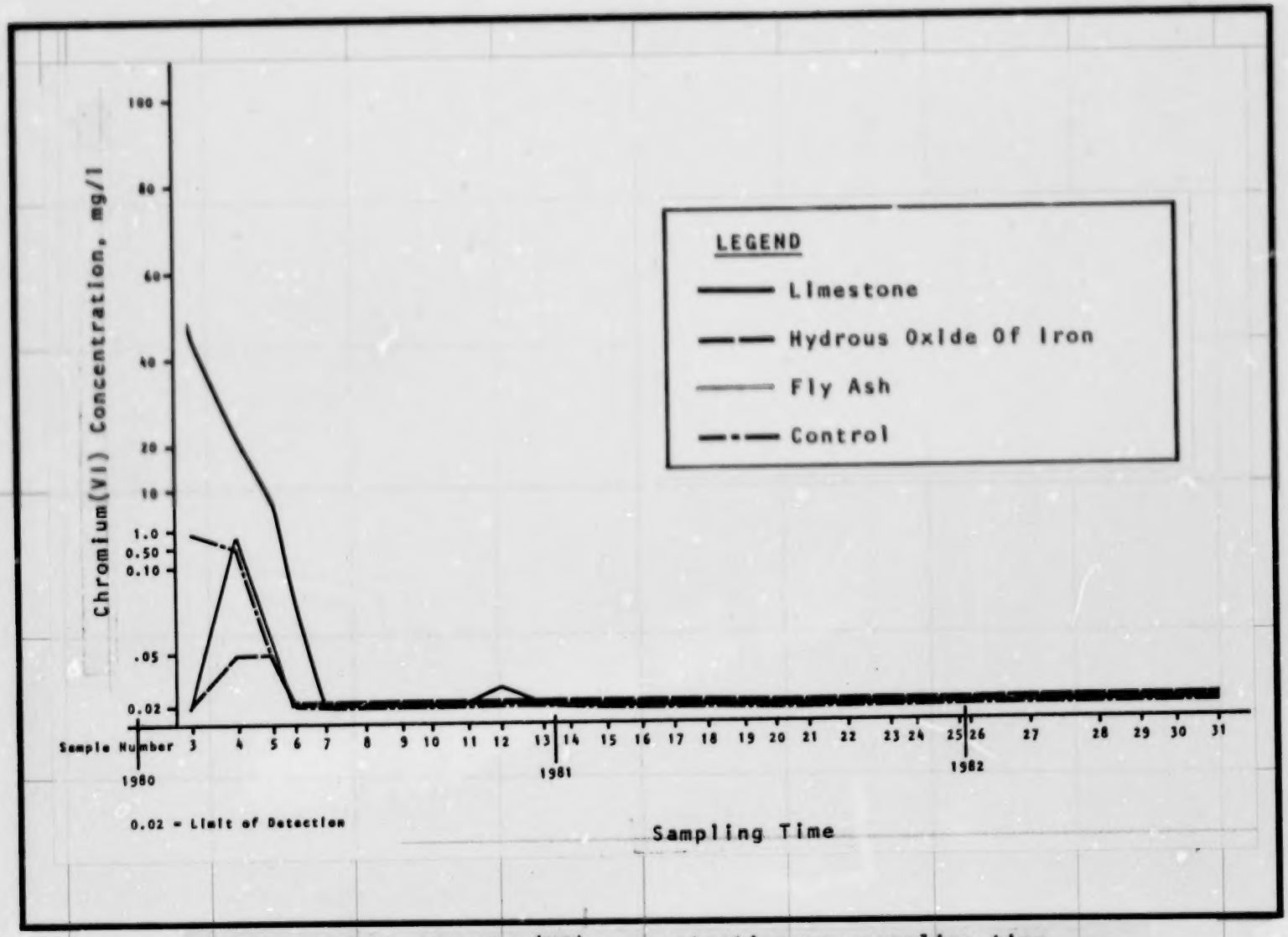

Figure 9 . Chromium(VI) concentration vs. sampling time.

5-7

(VI)

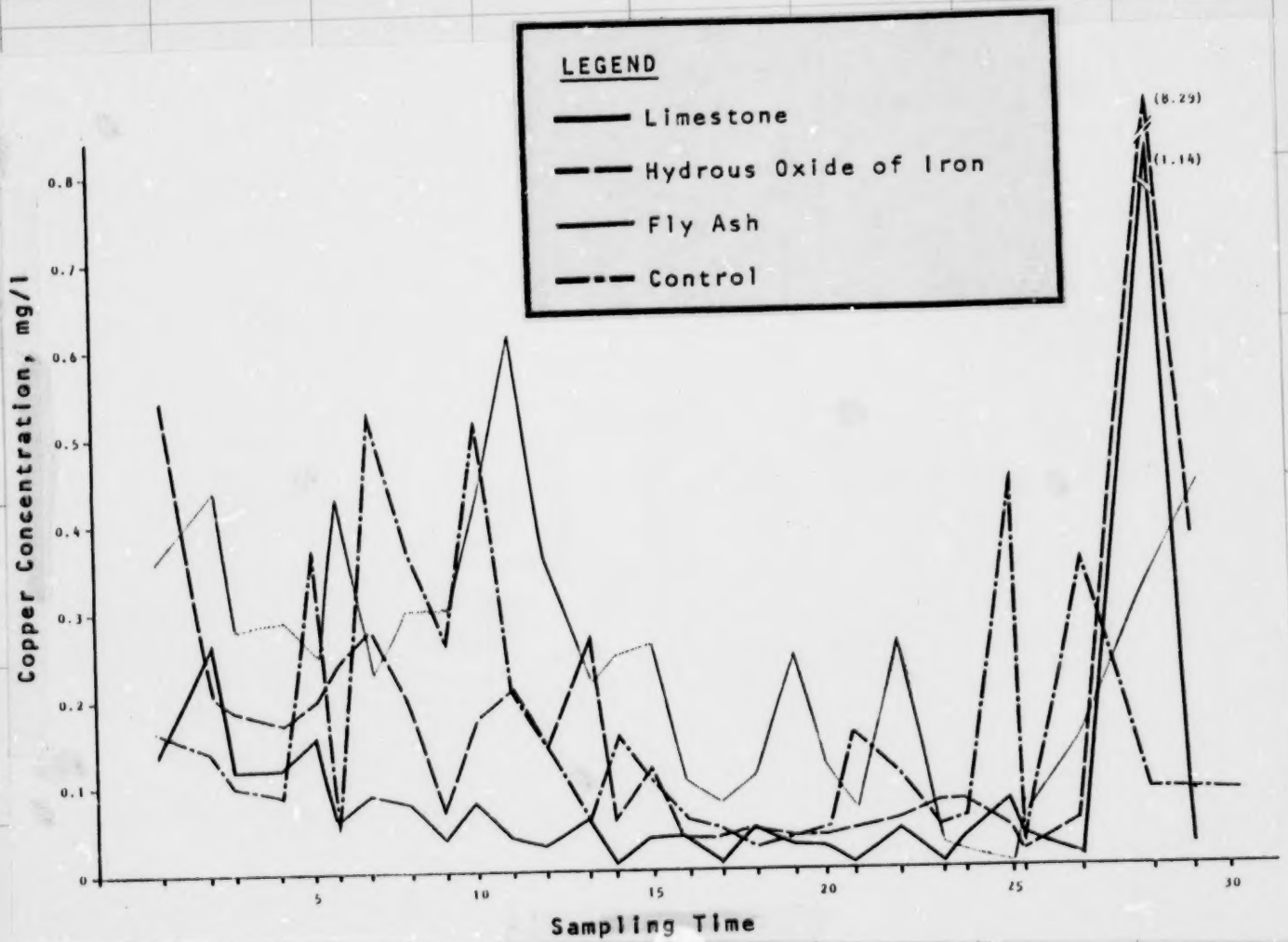

Figure 10. Copper concentration vs. sampling time.

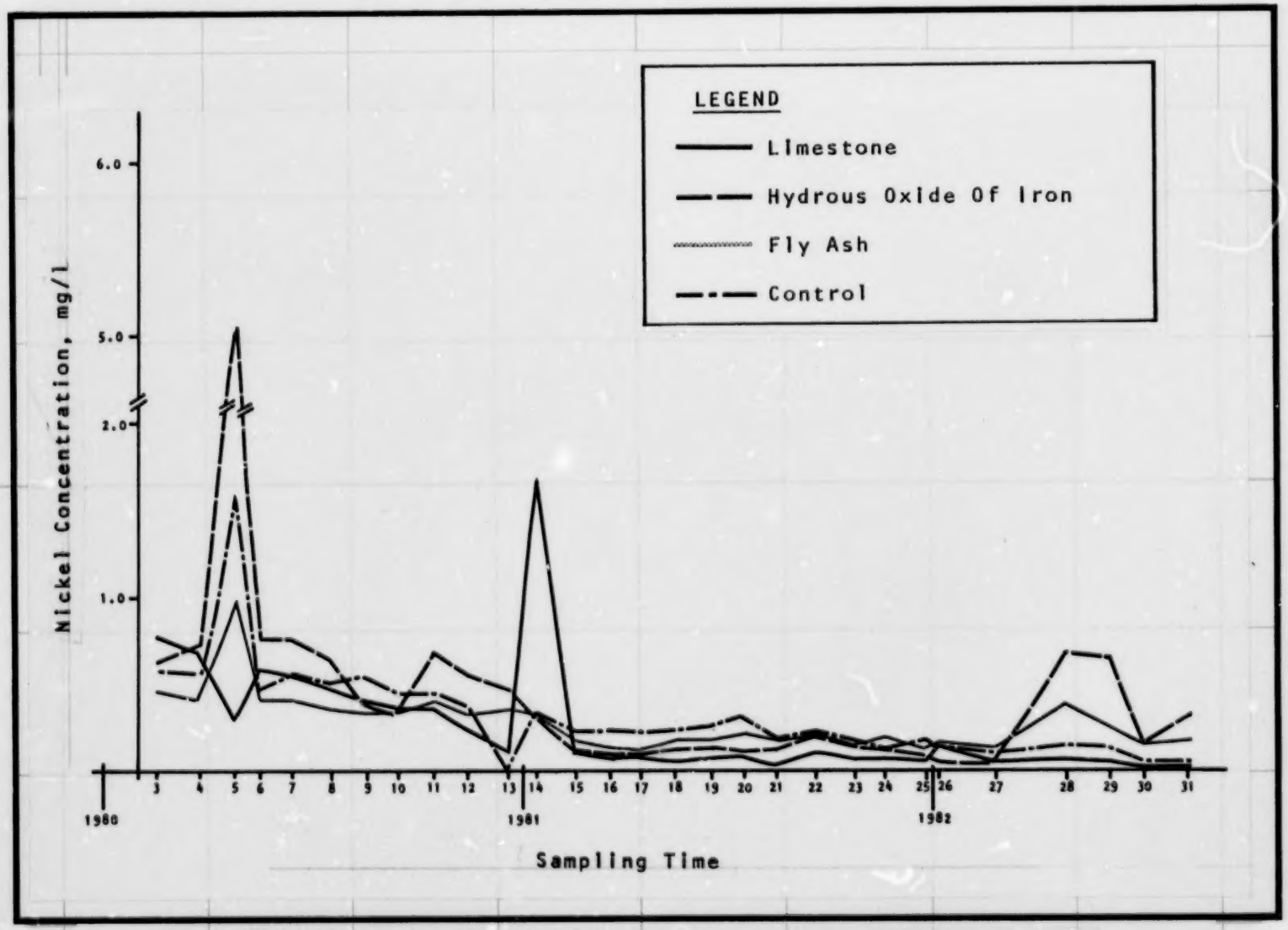

Figure 11. Nickel concentration vs. sampling time.

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5-10
37

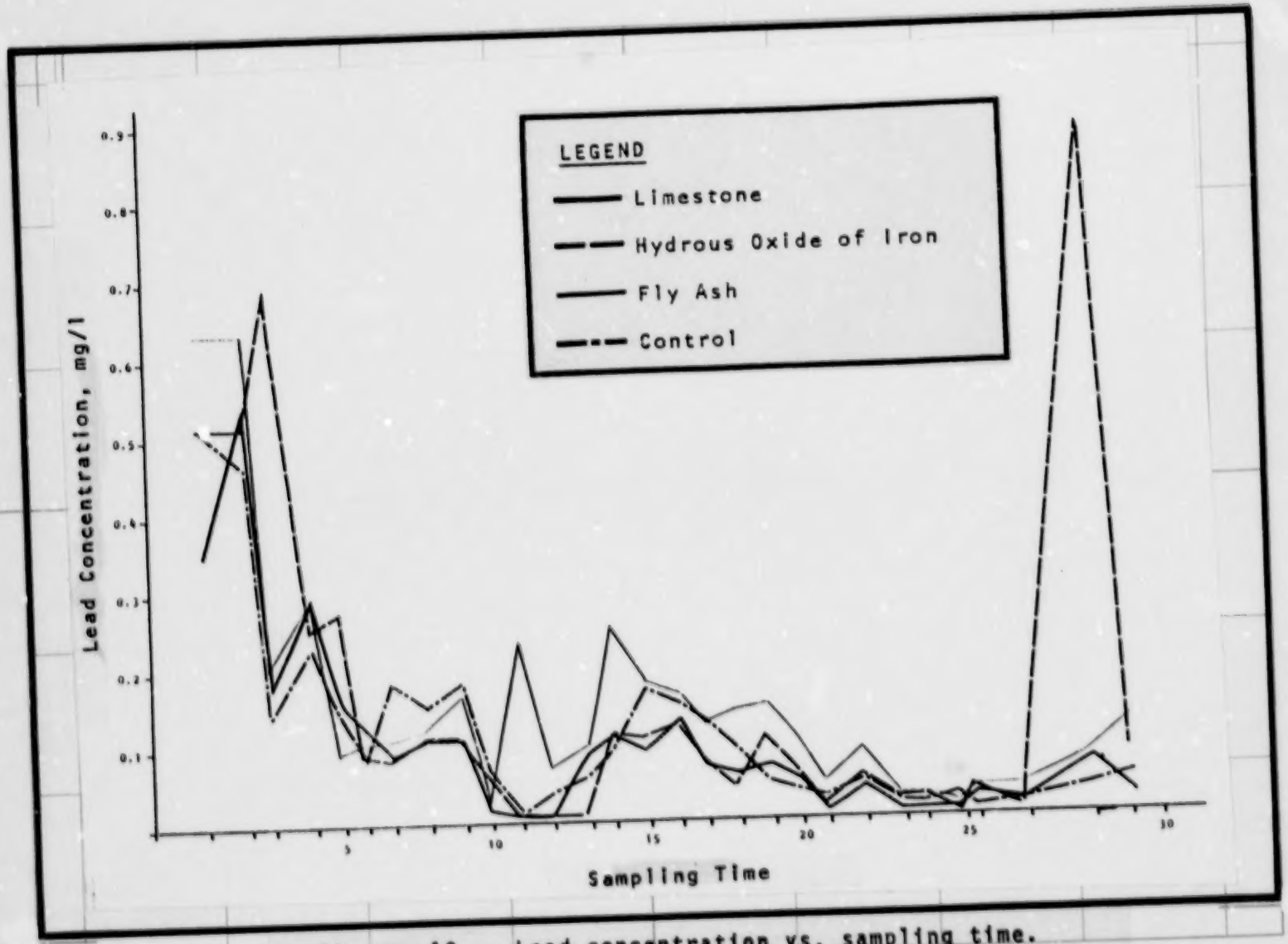

Figure 12 . Lead concentration vs. sampling time.

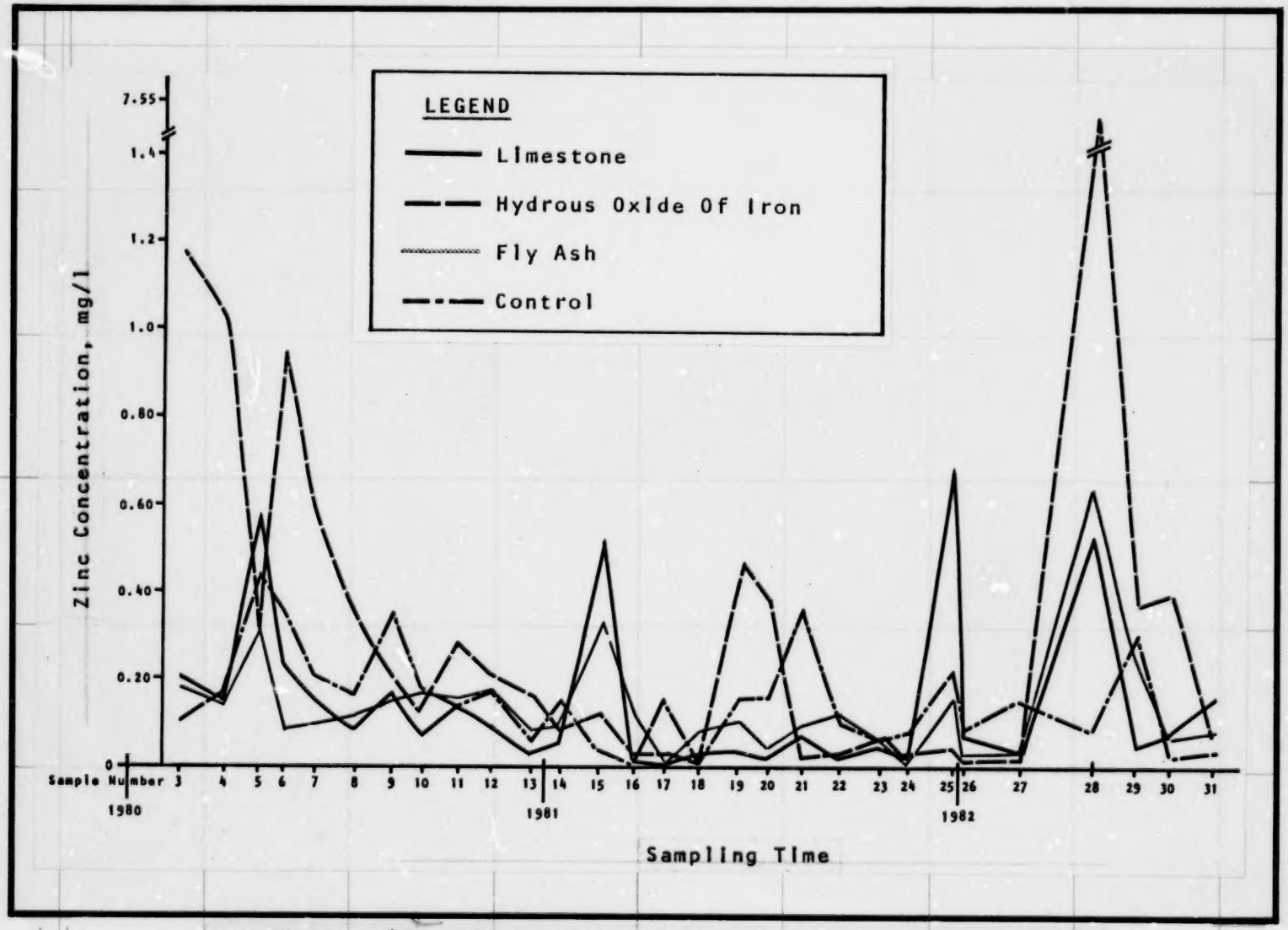

Figure 13. Zinc concentration vs. sampling time.

5-11.

obtained (after waiting and pumping again) were recorded (see Appendix A). Despite the problems encountered in obtaining them, these data did indicate the more porous nature of the limestone liners compared to the other two chemical liners. The fly ash liner, based on leachate volumes, proved to be the least permeable. In fact, the data suggests that the fly ash cells were most likely partially flooded throughout most of the evaluation period.

LEACHATE STATISTICS

Beginning in December 1980, the water depths and volumes of leachate removed during the monthly samplings were measured. These data are presented in Appendix A.

Cell water depth and volume of leachate pumped were examined in three ways:

1. Comparison of monthly values within each cell.
2. Comparison of values for corresponding months between replicate test cells.
3. Comparison of value for corresponding months between non-replicate test cells.

A 10-month period beginning December 1980, through and including August 1981, was examined. The results are shown in Table 7.

TABLE 7. LEACHATE VOLUMES FROM THE TEST CELLS*

Cell No.	Liner Type	Range	Median	Mean
		- - - - -	liters	- - - -
1	Native soil (control)	62-301	86	138
2	Limestone	80-550	305	279
3	Limestone	65-516	398	359
4	Fly ash	15-60	21	27
5	Fly ash	18-25	20	21
6†	Iron Oxides	33-348	91	141
7	Iron Oxides	26-57	40	39

* Data for December, 1980, to September, 1981.

† Cell No. 6 leachate volumes ranged from 33 to 91 l (avg. = 59 l) up to June 1981. The volumes for the next 3 months averaged 238 l.

These data illustrate the significant differences in cell hydraulic characteristics and indicate that the permeability of the liners are considerably different. While this latter fact was not unexpected, the apparent differences in hydraulic permeability among replicate cells (especially the iron oxide cells) reflect the physical differences in the test cells which may have occurred during construction. They may also reflect variations in sludge loadings or possible unexplained factors (short circuiting). The influence of varying hydraulic permeability values in trace metals flux thhrough the chemical liners could not be estimated due to these uncertainties.

Additionally, leachate volumes were examined as a function of rainfall (the only water added to the cells) (see Figure 3). No direct correlations were observed. This suggests that once the cells were charged with sufficient water, leachate production was more a function of cell and liner hydraulics than net amount of water added.

LEACHATE pH

The relative pH of the leachates generated in the control, limestone, and fly ash cells fluctuated greatly in the first 12 to 15 months; in the iron oxide cells, the pH showed a gradual increase (Figure 4). The leachate pH showed wide differences among the liners but had narrowed substantially beginning in March 1981. It appeared that the leachate pH was not controlled by the pH of any of the substances in the cell. Rather, it was the result of dissolution and retention of soluble salts, organic carbon, and heavy metals when rainwater percolated through the different layers (substances) in the cell.

The pH data suggest that the cells had reached a chemically stabilized condition beginning in March 1981, regardless of the liner used. As shown later, the concentration trends of the various heavy metals measured in the leachates tend to support this observation.

The actual pH of the leachates may have been more alkaline than reported due to the CO_2 blanket and purging used during leachate collection. Carbon dioxide was included in the project design to maintain the recovery of iron.

SOLUBLE SALTS

The levels of soluble salts in the leachates, as expressed by electrical conductivity (EC) values, decreased in all cells beginning in March 1981 (Figure 5). No EC measurements were made during 1980. The limestone cells had the lowest and the fly ash cells had the highest levels of soluble salts. The control and iron oxide cells fell between the other two chemical liners. All of the leachate EC measurements were high compared to typical potable waters in the United States (50 to 1500 umho/cm^3).

METAL CONCENTRATIONS IN LEACHATES

Iron (Fe)

Large concentrations of Fe were detected in the leachates from the iron oxide cells; the values peaked at 274 mg/l and decreased considerably thereafter (Figure 6). Iron was released gradually in the control and fly ash cells. The lowest concentration of Fe was found in the leachate from the limestone cells.

It has been reported that the maximum amount of Fe reduced under anaerobic conditions appears to be determined by the active Fe content and availability of organic matter; the pH is relatively unimportant (1). The sludge-borne Fe (primarily in solid-phase hydroxide) was not released (by reduction) to any great extent. This was probably due to the low organic matter content in the sludge. The high Fe content observed in the leachate of the iron oxide cells was principally from the chemical liner. Similar observations were noted by Fuller (2). Subsequent decreases in Fe concentration in these cells were thought to be due in part to the formation of iron sulfide which was observed during cell excavation. Although iron is generally considered a nuisance rather than a health hazard, the data indicate that it may not be desirable to line a landfill with hydrous oxides of iron due to Fe enrichment of leachate.

Manganese (Mn)

The concentrations of Mn in the leachates from the seven cells were low (<5 mg/l for all but 2 readings), but fluctuated throughout the sampling period (Figure 7). This was attributed to the low Mn content of the sludge, since the reduction of Mn and its release into the soil solution is controlled primarily by the Mn content of the soil (or sludge) (1). The iron oxide cells released Mn in the first few months, while the fly ash reversed this trend. The concentration trends of Mn with respect to liner types were similar to those of Fe: the highest and lowest concentrations were found in the iron oxide and limestone cells, respectively.

Chromium (Cr)

The concentrations of Cr(III) in the leachates from the limestone cells were elevated in the first few months and decreased thereafter (Figure 8). Cr(VI) followed a similar trend in the limestone cells (Figure 9). No Cr(VI) was detected (<0.02 mg/l) in the iron oxide cells; none of the cells showed any detectable Cr(VI) after eight months (Figure 9). The reasons for the high levels of Cr(III) and Cr(VI) in the limestone cells and, to a lesser extent, the control and fly ash cells are not clear but were probably due to cumulative leaching during rainstorms while the open cells were being filled with sludge. In view of

the large amount of Cr(III) in the raw sludges, the concentrations of Cr(III) in the leachate indicate that no significant leaching of this species from the sludges had occurred. Because of the low leachability of Cr(III), the ability of various chemical liners to retain this contaminant cannot be determined. In a laboratory column study, Artiola and Fuller (3) reported that crushed limestone was more effective in retarding the migration of Cr(III) than Cr(VI), Cd, Ni, and Zn, when leachate from municipal solid waste spiked with these metals was used.

Because of the high pH of the sludges, Cr was present primarily as Cr(III). The more mobile specie, Cr(VI), was not a significant species in terms of concentration. Cr(VI) was retained principally by the iron oxide through its conversion to Cr(III) by an electron donor, Fe(II). However, due to the high leachate pH, no significant leaching of Cr(VI) was detected following its initial release in the limestone, fly ash, and control cells. The ability of the three liners tested in retaining Cr(VI) cannot be determined from the leachate data.

Other Metals

The concentrations of copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn) in the leachate over sampling time are presented in Figures 10, 11, 12, and 13, respectively. Although the concentrations of these metals in the leachate fluctuated over the sampling time, their relationship to the metal concentrations in the raw sludges is uncertain. When compared to drinking water standards, cadmium (Cd) and Pb exceeded the allowable limits (0.01 and 0.05 mg/l), whereas Cu and Zn did not (1.0 and 5.0 mg/l). Nickel concentrations, for the most part, were less than 0.5 mg/l.

On the average, the limestone cells appeared to have resulted in leachate with the lowest metal concentrations. The fly ash and control cells produced leachates with higher metal concentrations than those of the other test cells. These observations cannot be substantiated statistically.

METAL DISTRIBUTION IN TEST CELLS

To estimate the extent of leaching of heavy metals and their retention by the chemical liners, core samples obtained at the end of the leachate monitoring were sectioned and analyzed. Because of the compaction during boring, the depths of the various layers observed are not representative of those that occurred in the cell. The surface soil was removed prior to boring and thus was not part of the core sample.

It should also be noted that these borings may not be truly representative of the cells as they were filled. Reasons for this are as follows:

- Sludges were added to the cells over a 6-8 week period which was frequently interrupted by heavy downpours.

- This fact, coupled with the varying sludge densities (Crescent sludge - 17% solids; Wolverine sludge - dried solids), may account for some of the observed discrepancies in layers if partial flooding had occurred.

- Sludges were added to the cells when sufficient quantities had been stockpiled so that equal distribution would be achieved. It was not the original intent of the project to have clearly defined sludge layers.

- The size of the cells made thorough mixing impossible. The horizontal distribution of sludges was poor, resulting in probable discontinuities. Therefore, multiple core samples would have to be withdrawn from each cell to produce an "average" value.

Control Cell

The concentrations of heavy metals found in the different layers in the control cell (No. 1) are presented in Table 8. A schematic of the layers is shown in Figure 14. This sludge was blue-green in color and was moist (not saturated) when removed from the cell. The data showed that part of the surface soil may have been added during site grading. This soil was highly acidic (pH 3.7) and contained high concentrations of iron, typical of the native soils. The core top soil was slightly contaminated with sludge leachate, as indicated by the pH value which is higher than that of the surface soil.

To a large extent, the heavy metals were still retained in the Wolverine Brass sludge. The reasons for only observing one layer of sludge are unclear. About 5,200 kg of each sludge were originally added to this cell. The data suggests that the Crescent sludge, originally the bottom layer, may have been compacted into the sand layer. The subsequent extraction of the sand-gravel layer, utilizng 0.5 N HCl, may not have been sufficiently severe to judge this layers true chemical content.

Additionally, only one core sample was removed from this cell. The possibility exists that it was not representative of the cell conditions.

Limestone Cells

The distribution of heavy metals in the two limestone cells (Nos. 2 and 3) is given in Tables 9 and 10, respectively. Schematics of the different layers are shown in Figures 15, 16, and 17.

The surface soil was highly acidic with high Fe concentrations similar to that in the control cell. Four sludge layers were observed in the first limestone cell (No. 2) (Figure 15). The first and third sludge layers in this test cell appeared to be similar to Crescent Tool Sludge, as suggested by similar

TABLE 8. DISTRIBUTION OF HEAVY METALS IN CELL NO. 1, CONTROL

Cell Layer	pH	Fe	Ni	Zn	Mn	Pb	Cd	Cu	Cr(VI)	Cr(III)	Hg	H_2O** (%)
		(mg/kg*)										
Surface Soil	3.7	10,770	1.43	2.64	5.75	6.43	<0.02	4.51	0.24	15.8	<0.02	27.6
Core Topsoil	5.5	8,788	1.28	1.13	6.10	6.19	<0.02	4.14	0.17	18.1	0.12	27.6
Sludge†	8.0	5,393	17,838	16,954	96.5	878	283	24,109	143	33,486	0.60	84.2
Sand & Gravel	7.1	237	0.86	0.96	2.06	0.27	0.02	9.75	0.13	2.41	NA#	10.1

* Oven-dry weight basis.

† Wolverine Brass sludge.

\# NA = Not analyzed.

** Calculated as a function of dry weight.

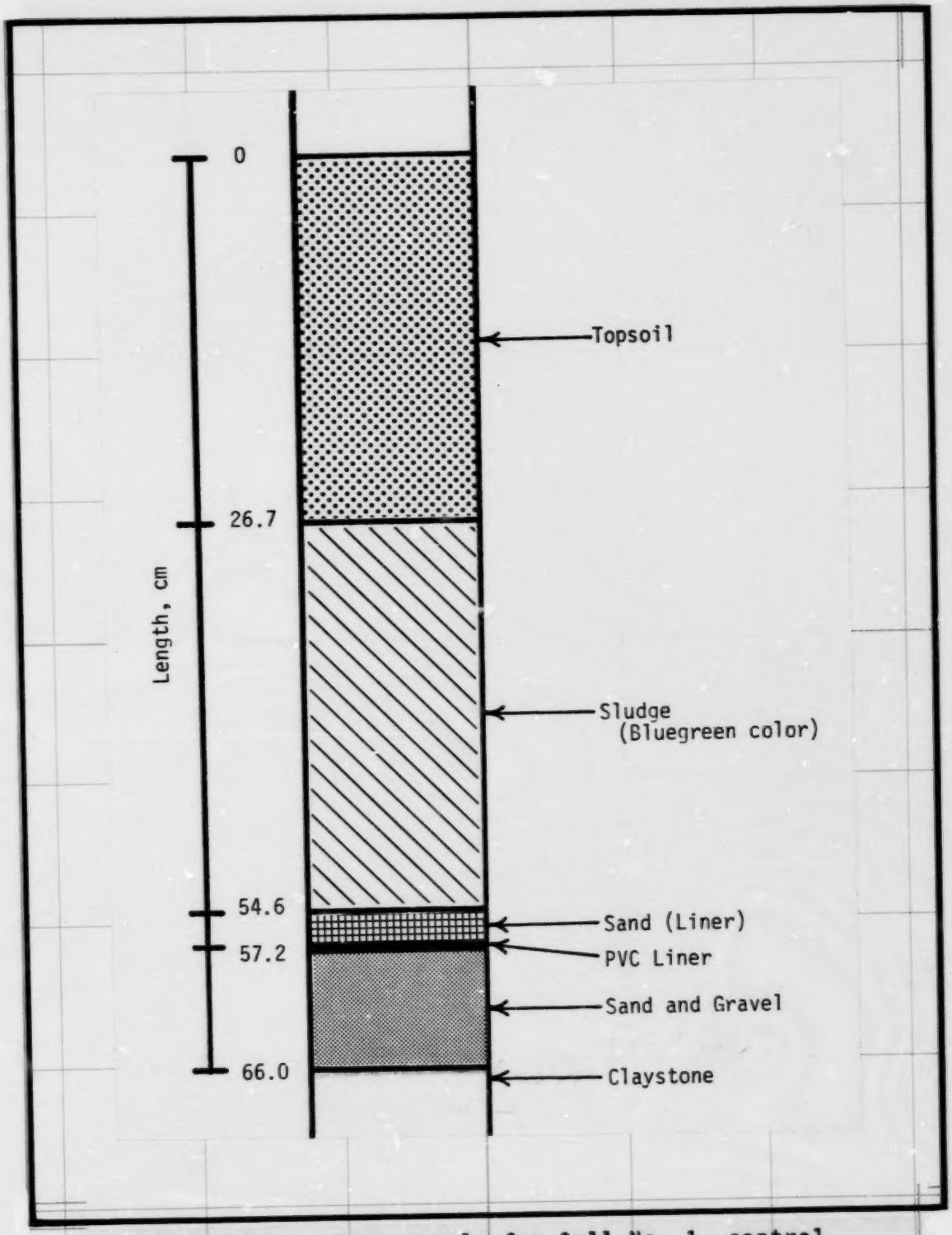

Figure 14 . Core sample for Cell No. 1, control.

TABLE 9. DISTRIBUTION OF HEAVY METALS IN CELL NO. 2, LIMESTONE LINER

Cell Layer	pH	Fe	Ni	Zn	Mn	Pb	Cd	Cu	Cr(VI)	Cr(III)	Hg	H_2O# (%)
		(mg/kg*)										
Surface Soil	3.8	11,206	2.02	2.02	4.78	8.16	0.20	4.08	0.14	13.86	0.13	32.0
Sludge Layer No. 1 (C)†	7.0	65,563	77,638	44,008	1,183	1,254	104	26,074	9.64	46,059	1.02	376
Sludge Layer No. 2 (M)†	7.8	16,694	10,994	23,172	292	5,186	1,562	33,194	64.7	24,272	0.55	210
Sludge Layer No. 3 (C)†	7.1	104,879	54,416	47,759	1,868	601	19.7	10,965	0.61	47,203	0.75	399
Sludge Layer No. 4 (W)†	7.8	3,179	13,578	18,975	58.1	1,129	28.4	26,165	183	39,241	0.12	90
Limestone Liner	8.1	164	20.5	10.5	84.6	16.0	2.0	20.8	0.17	3.54	0.22	13.7

* Oven-dry weight basis.

† C = Crescent Tool sludge; W = Wolverine Brass sludge; M = mixture of the two sludges.

Calculated as a function of dry weight.

TABLE 10. DISTRIBUTION OF HEAVY METALS IN CELL NO. 3, LIMESTONE LINER

Cell Layer	pH	Fe	Ni	Zn	Mn	Pb	Cd	Cu	Cr(VI)	Cr(III)	Hg	H_2O** (%)
		(mg/kg*)										
Surface Soil	3.6	14,005	6.75	10.14	6.44	10.14	0.16	4.17	0.08	19.6	0.17	25.9
Core Topsoil	4.1	17,954	121	135	7.80	14.52	0.24	36.2	0.05	115	0.37	45.1
Sludge Layer No. 1 (C)†	7.1	64,933	45,876	59,641	1,160	1,368	705	17,710	33.13	56,061	0.81	298
Sludge Layer No. 2 (W)†	7.9	7,184	15,449	24,001	121.4	787.4	150.4	33,515	77.57	37,490	0.20	75
Limestone Liner	7.7	320	14	5.80	111	20.1	2.07	4.81	0.16	3.86	0.5	14.4
Sand & Gravel	7.9	64.73	38.8	49.3	3.24	3.90	0.15	87.2	0.27	57.7	NA#	5.8

* Oven-dry weight basis. Sludge data are averages of two core samples (A and B).

† C = Crescent Tool sludge; W = Wolverine Brass sludge.

\# NA = Not analyzed.

** Calculated as a function of dry weight.

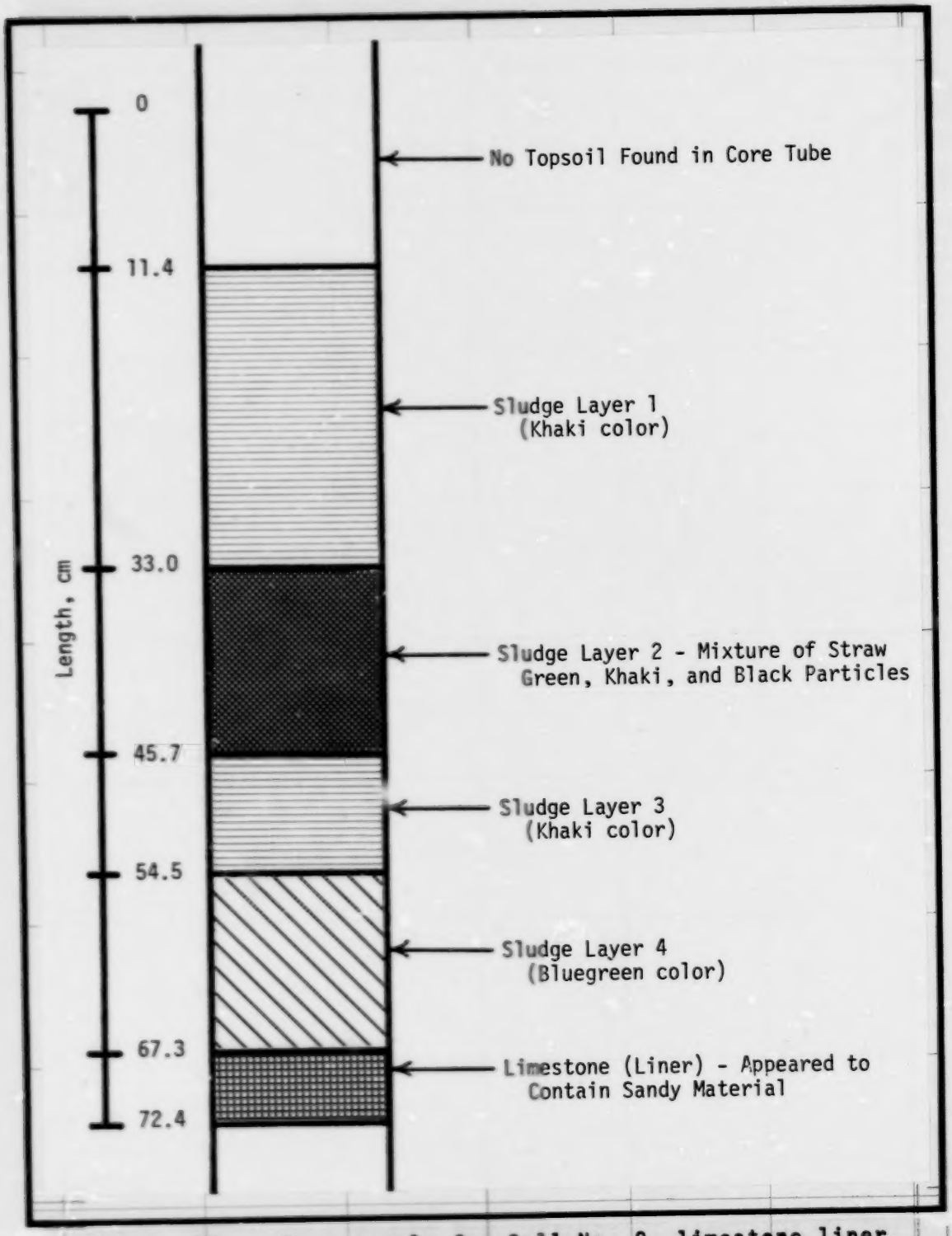

Figure 15 . Core sample for Cell No. 2, limestone liner.

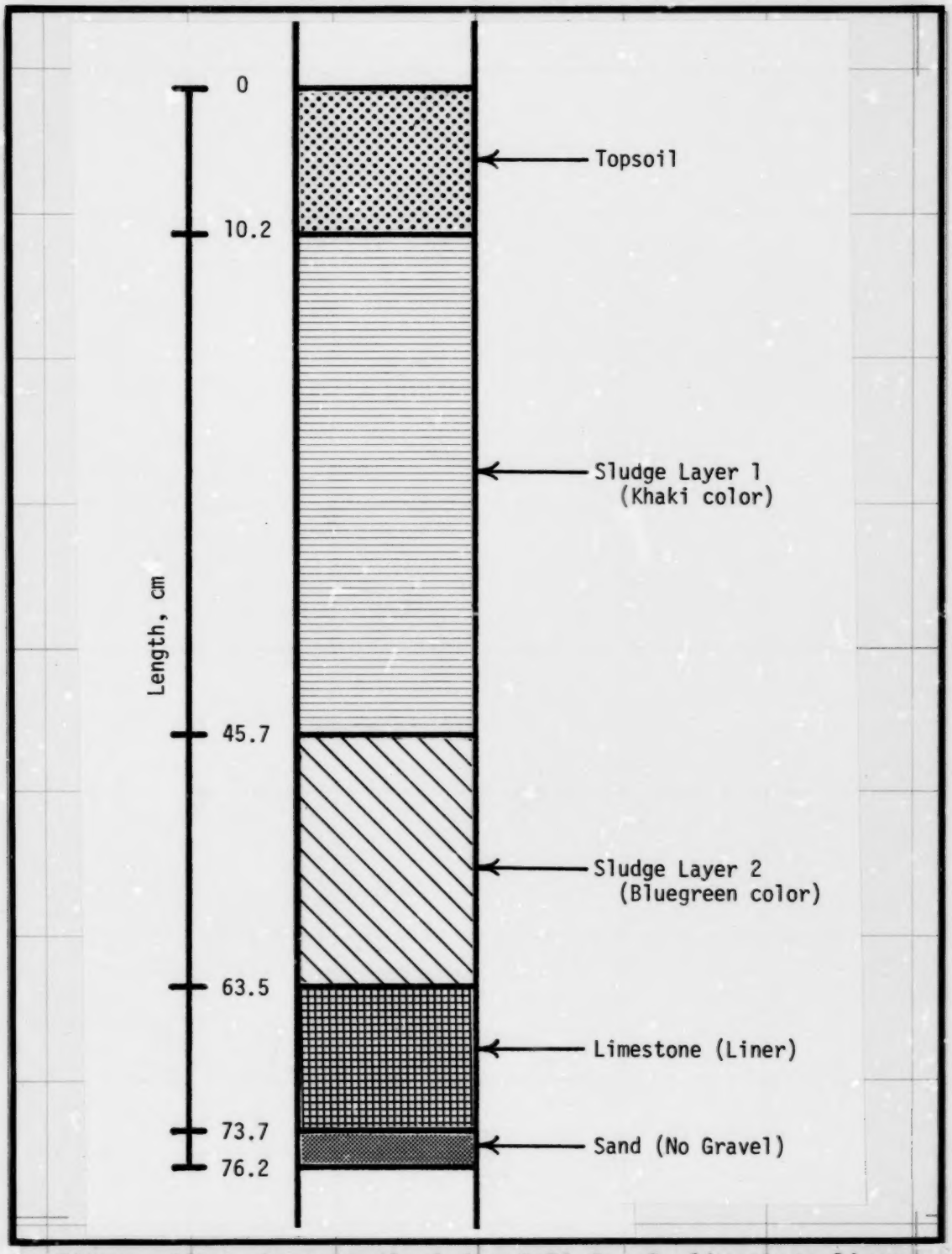

Figure 16 . Core sample A for Cell No. 3, limestone liner.

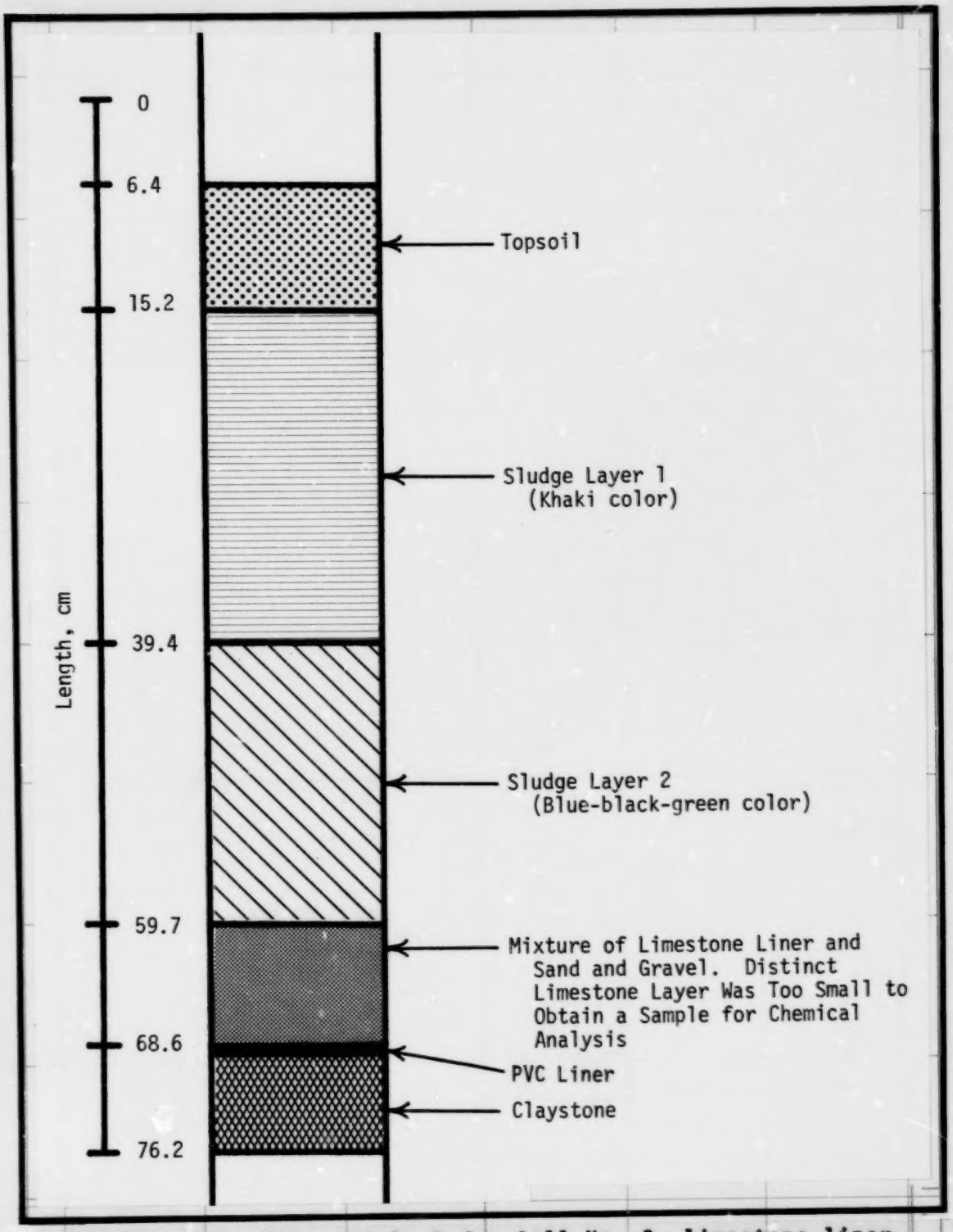

Figure 17 . Core sample B for Cell No. 3, limestone liner.

color, pH (7.0), moisture content, and high concentrations of Fe, Ni, Zn, Cu, and Cr(III). The fourth layer of sludge resembled Wolverine Brass sludge which was similar to the sludge in the control cell boring; namely, blue-green in color, pH of 7.8 to 8.0, lower moisture content, and lower levels of Fe, Ni, Zn, and Mn. The second sludge layer seemed to be a mixture of the two sludges but exhibited metal concentrations (e.g., Ni, Pb, Cu, and Cr(III)) more resembling the Wolverine sludge. Most of the Cr was in the Cr(III) form. The limestone liner was contaminated with heavy metals to various degrees; the highest concentrations were found for Fe and Mn and the lowest for Cr(VI).

Two core samples were obtained from the second limestone test cell (No. 3) (Figures 16 and 17). There were two sludge layers in each core: the first layer was similar to Crescent Tool sludge; the second similar to Wolverine Brass sludge. No mixed sludge layer was found in this test cell. The average metal concentrations from the same type of sludge are given in Table 10. These concentrations were similar to those in the first limestone cell for the respective types of sludges. Similar observations were found in the limestone liner. Concentrations of heavy metals in the sand/gravel layer (underlying the PVC membrane) were probably indicative of the characteristics of the leachate that contaminated this layer during cell excavation.

Overall, based on the large concentrations of various heavy metals in the sludges and the small concentrations in the limestone liner, it appears that no significant leaching had occurred in the two limestone test cells.

Fly Ash Cells

The distribution of heavy metals in the two fly ash cells (Nos. 4 and 5) is given in Tables 11 and 12. Schematics of the different layers in the cells are shown in Figures 18, 19, and 20.

There were seven distinct layers in the core sample taken from Cell No. 4 (Figure 18). For metal analysis, two sludge composites representing the two sludge types were made. The surface soil layer in Cell No. 4 contained larger concentrations of heavy metals (e.g., Ni, Zn, and Cr) than the same layers in the other six test cells, suggesting that this layer had been contaminated or flooded with sludge leachate. This may be a result of the reduced permeability previously noted. Except for pH, the surface soil and the topsoil layers showed similar metal concentrations.

The two sludge layers in the first fly ash cell (No. 4) exhibited characteristics typical of the two respective sludge types. When compared to the same types of sludge from the other test cells, it appeared that no appreciable leaching of heavy metals had occurred in this cell. Different amounts of heavy

TABLE 11. DISTRIBUTION OF HEAVY METALS IN CELL NO. 4, FLY ASH LINER

Cell Layer	pH	Fe	Ni	Zn	Mn	Pb	Cd	Cu	Cr(VI)	Cr(III)	Hg	H_2O** (%)
		(mg/kg*)										
Surface Soil	3.8	11,728	92.0	154	12.4	7.59	0.22	25.9	0.04	96.5	0.17	30.2
Core Topsoil	5.0	13,530	98.0	107	7.46	8.40	0.10	24.5	0.10	54.4	0.13	31.4
Sludge Layer Nos. 1 & 3 - Composite (C)†	6.8	111,824	43,924	83,965	2,043	422	14.7	6,436	0.45	40,896	0.20	408
Sludge Layer Nos. 2 & 4 - Composite (W)†	7.9	11,791	5,697	25,694	168	7,624	4,959	35,127	72.1	32,136	0.10	249
Fly Ash Liner	5.8	8,652	25.2	34.5	41.5	14.5	0.43	54.6	0.10	29.6	<0.02	33.8
Sand & Gravel	8.0	13.2	1.33	1.63	0.38	0.16	<0.01	1.49	<0.02	<0.02	NA#	8.0

* Oven-dry weight basis.

† C = Crescent Tool sludge; W = Wolverine Brass sludge.

\# NA = Not analyzed.

** Calculated as a function of dry weight.

TABLE 12. DISTRIBUTION OF HEAVY METALS IN CELL NO. 5, FLY ASH LINER

Cell Layer	pH	Fe	Ni	Zn	Mn	Pb	Cd	Cu	Cr(VI)	Cr(III)	Hg	H_2O# (%)
		(mg/kg*)										
Surface Soil	3.6	11,787	48.11	35.0	7.94	8.51	0.59	17.7	0.13	43.6	0.25	31.9
Topsoil	4.3	11,202	69.32	45.54	9.73	11.17	2.20	48.11	0.48	76.86	<0.02	31.7
Sludge (M)†	7.8	43,724	29,540	35,238	739.1	1,063	2,041	17,318	80.50	39,117	0.33	258
	7.7	70,411	45,263	48,217	1,383	693	1,112	12,068	61.0	44,413	0.36	347
Fly Ash Liner	6.2	6,231	20.1	28.5	49.2	16.4	0.40	37.4	0.09	19.9	0.05	36.8
Sand & Gravel	6.4	321	2.98	7.24	4.69	0.61	0.10	2.70	0.02	3.22	0.32	12.1

* Oven-dry weight basis.

† M = Mixture of Crescent Tool and Wolverine Brass sludges.

\# Calculated as a function of dry weight.

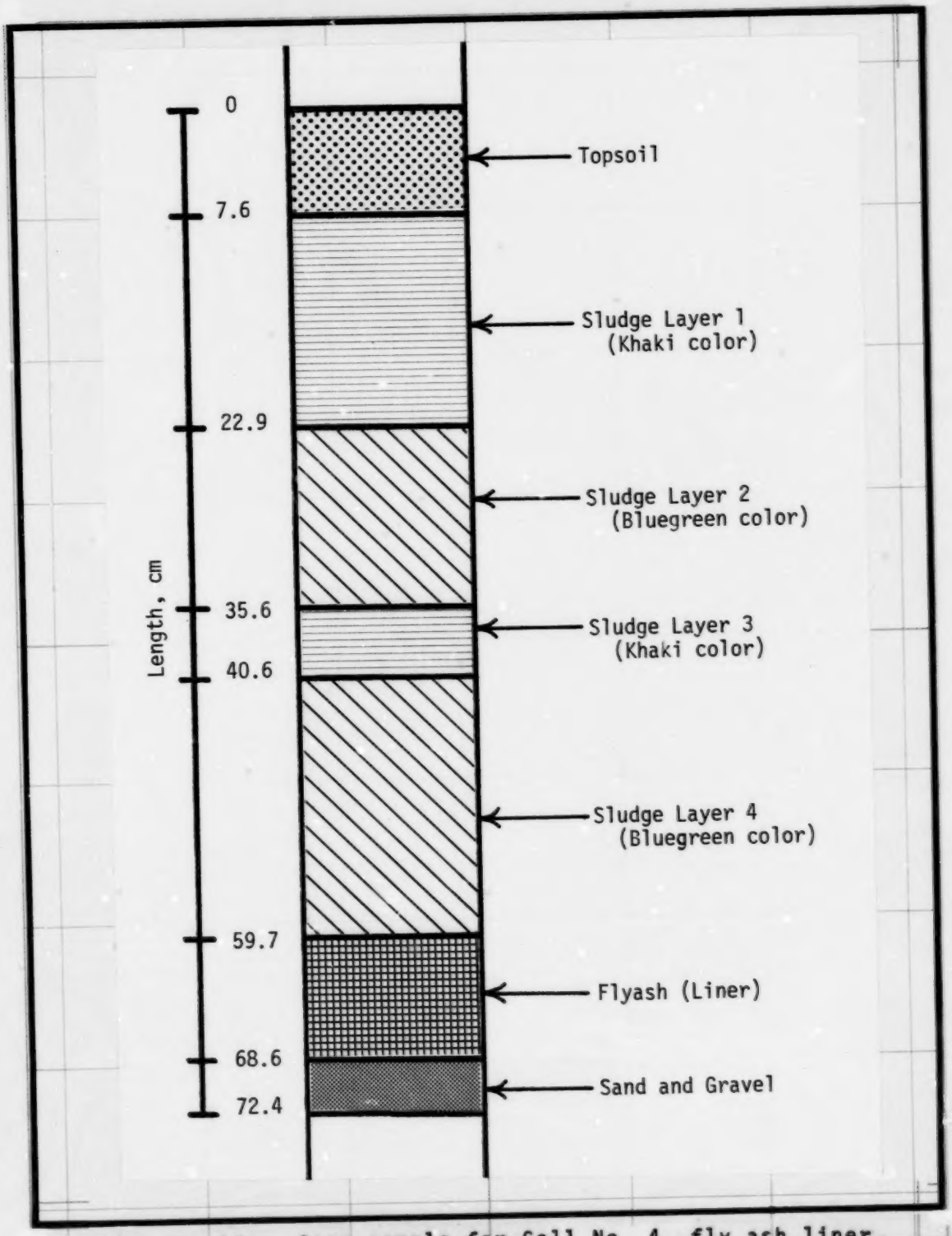

Figure 18. Core sample for Cell No. 4, fly ash liner.

metals were retained in the fly ash layer. However, this retention showed no relationship to the total metal concentrations in the sludges.

There were five layers in the second fly ash cell (No. 5) (Figures 19 and 20). A composite of two sludge layers was made for metal analysis. The sludge data shown in Table 12 are the average of two core samples from Cell No. 5. The surface soil layer contained lower concentrations of Ni, Zn, Cu, and Cr(III) than the same layer in Cell No. 4. While similar trends of Ni and Zn were observed in the topsoil layer of the two cells, the opposite was observed for Cu and Cr(VI). Variability of this magnitude is common considering the contacts of the soil with sludge and leachate in the cells. The first fly ash cell appeared to have retained greater amounts of heavy metals than the second fly ash.

Iron Oxide Cells

The distribution of heavy metals in the two iron oxide cells (Nos. 6 and 7) is given in Tables 13 and 14; schematics of the different layers in the cells are shown in Figures 21 and 22. The coverings show similar differences as previously described for other cells. It appears as if compaction during coring was responsible for some of these variations. For example, the analysis of sludge layer No. 2 from test cell No. 7 includes some iron oxide (Fe = 100,700 mg/kg).

When the surface soil and core topsoil in the two iron oxide cells were compared, higher metal concentrations (in particular, Ni, Zn, Cu, and Cr(III)) were detected in Cell No. 6 than Cell No. 7.

The iron oxide layer in the two cells retained various amounts of heavy metals, noticeably Ni and Cr(III). The Fe concentration had decreased considerably, as substantiated by its large release into the leachate. Black metal sulfide precipitates were observed in the iron oxide layer. The sulfide, formed by sulfate reduction, was partially responsible for metal retention observed in these test cells. The low leaching rate (high water retention) may have been responsible for the extended anaerobic condition leading to the sulfide formation.

METAL RETENTION BY CHEMICAL LINERS

Assuming that the leachability of the sludges from the seven test cells was similar, the ability of the chemical liners to retain heavy metals may be evaluated on the basis of metal concentrations in the leachate and/or the chemical liners. Logically, the larger the concentrations of metals retained in a liner under experimental conditions the better performance of the liner.

The leachate data indicate elevated releases of metals initially, but the concentrations leveled off after the first year.

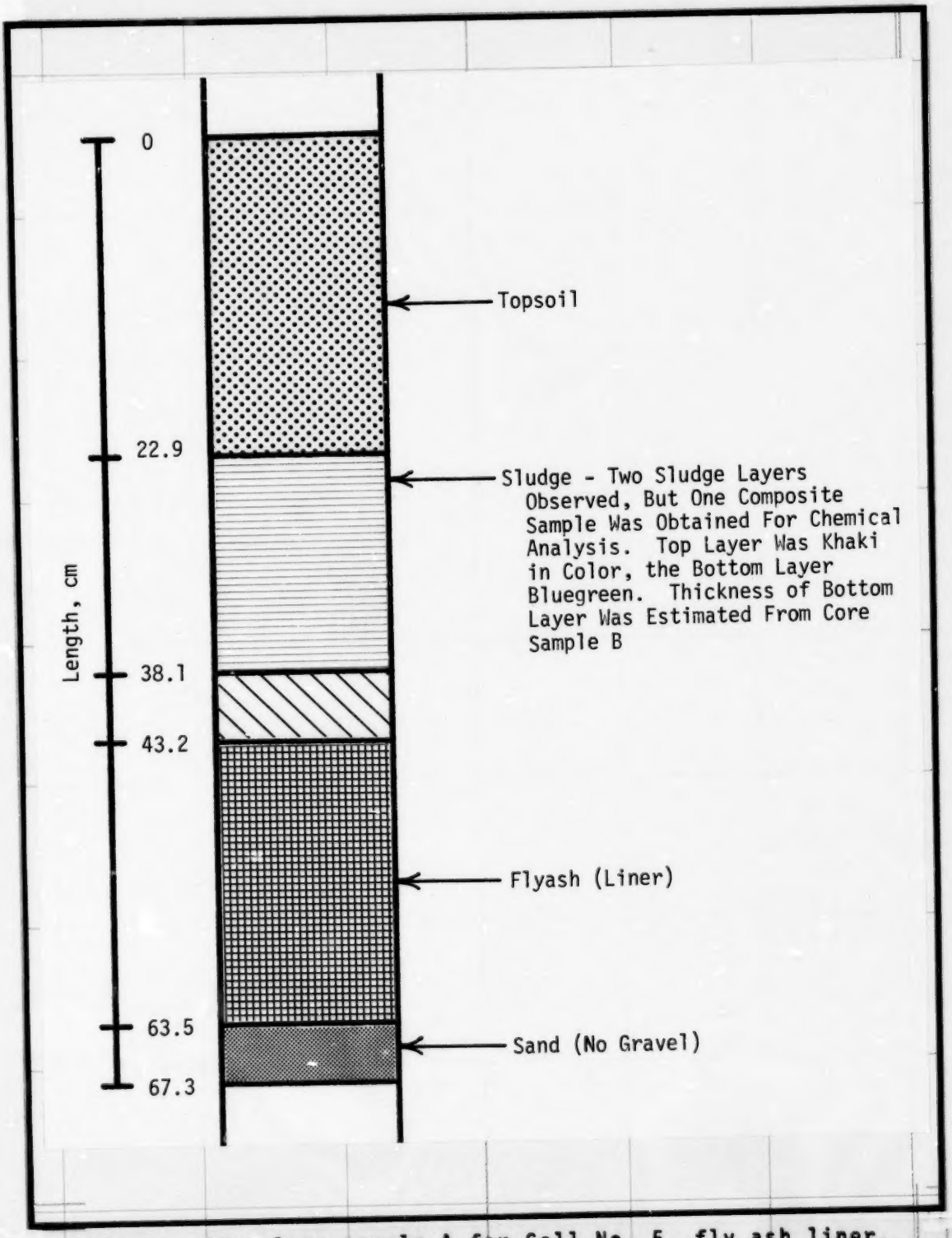

Figure 19 . Core sample A for Cell No. 5, fly ash liner.

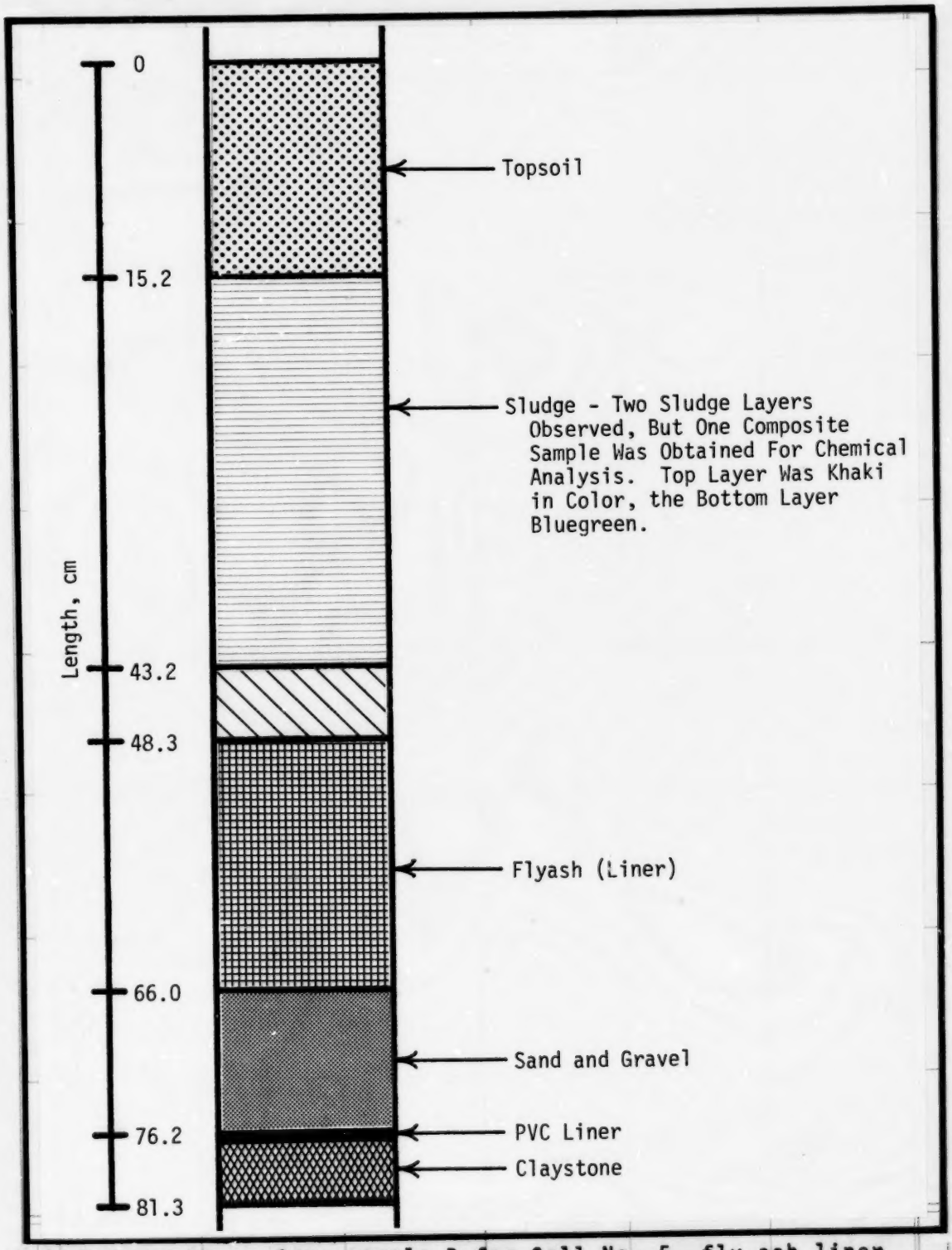

Figure 20 . Core sample B for Cell No. 5, fly ash liner.

TABLE 13. DISTRIBUTION OF HEAVY METALS IN CELL NO. 6, IRON OXIDE LINER

Cell Layer	pH	Fe	Ni	Zn	Mn	Pb	Cd	Cu	Cr(VI)	Cr(III)	Hg	H_2O** (%)
		(mg/kg*)										
Surface Soil	3.8	11,950	12.4	8.96	9.56	6.09	<0.02	9.14	0.19	27.5	0.15	30.8
Core Topsoil	6.0	12,175	544	61.7	9.33	20.8	1.49	513	0.18	633	0.18	34.5
Sludge (W)†	7.8	5,853	14,084	14,924	70.1	722	49.0	19,592	72.6	21,161	0.67	82.7
Sand & Gravel Layer - Light Colored	7.8	62.6	53.1	42.1	0.71	5.87	0.29	56.7	0.29	46.3	NA#	5.5
Sand & Gravel Layer - Dark Colored	7.1	137	3.72	3.02	3.06	<0.01	<0.01	3.83	0.07	6.26	NA#	6.9

* Oven-dry weight basis.

† W = Wolverine Brass sludge.

\# NA = Not analyzed.

** Calculated as a function of dry weight.

TABLE 14. DISTRIBUTION OF HEAVY METALS IN CELL NO. 7, IRON OXIDE LINER

Cell Layer	pH	Fe	Ni	Zn	Mn	Pb	Cd	Cu	Cr(VI)	Cr(III)	Hg	H_2O** (%)
		(mg/kg*)										
Surface Soil	3.7	10,432	1.24	2.69	9.27	8.15	0.12	3.96	0.04	11.4	0.20	27.9
Core Topsoil	4.1	13,542	15.8	25.4	8.25	8.64	1.21	47.5	0.64	49.0	NA#	42.8
Sludge Layer No. 1 (W)†	7.9	4,811	12,042	20,765	73.5	632	102	29,766	160	35,420	0.15	79.8
Sludge Layer No. 2 (C)†	7.4	100,740	56,555	30,874	1,494	274	13.4	2,535	0.05	43,596	0.35	478
Iron Oxide, Sand & Gravel Layers, Mixed	6.4	326	68.6	31.9	2.87	1.14	0.06	7.23	0.05	38.4	NA#	9.8

* Oven-dry weight basis.

† W = Wolverine Brass sludge; C = Crescent Tool sludge.

\# NA = Not analyzed.

** Calculated as a function of dry weight.

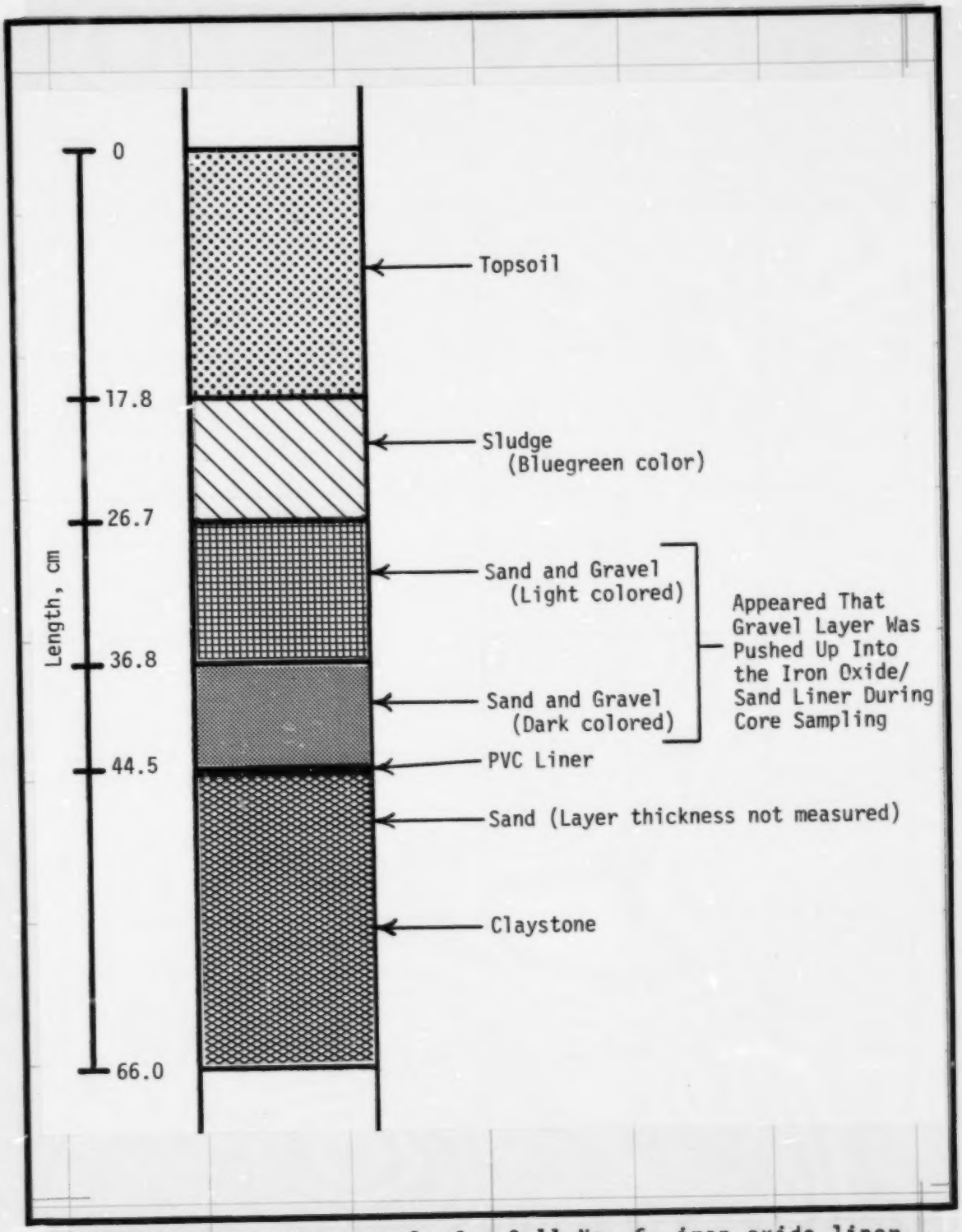

Figure 21 . Core sample for Cell No. 6, iron oxide liner.

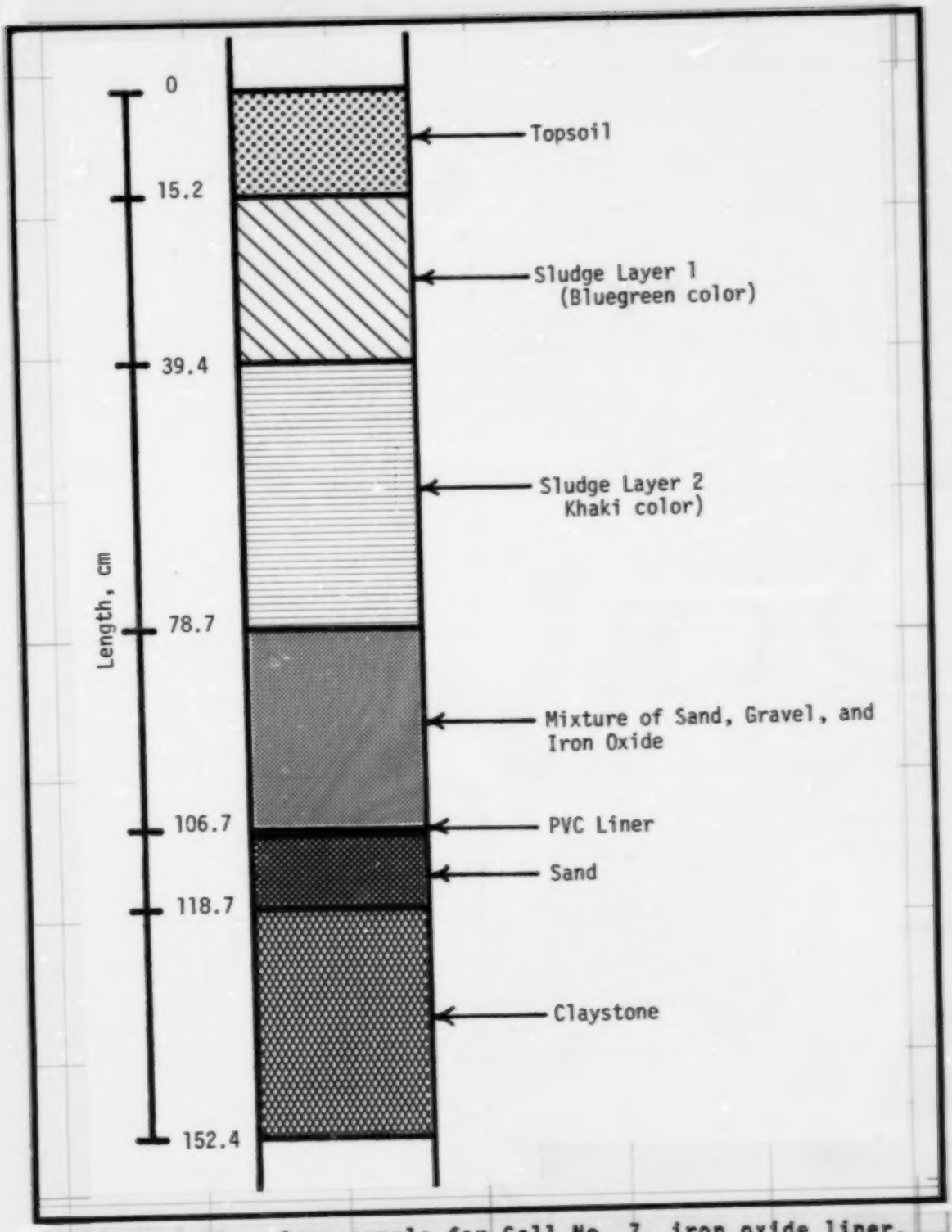

Figure 22. Core sample for Cell No. 7, iron oxide liner.

Leachates from the limestone cells appeared to have the lowest metal concentrations among the three chemical liners. However, for a majority of metals, the differential is so small that it would not be possible to judge the performance of the liners based on leachate data.

The sludge data indicate that very little leaching of heavy metals had occurred. This was due in part to the high pH and to the hydroxides in which the metals were present. Concentrations of the different metals retained in the chemical liners are shown in Table 15. Since raw fly ash contained low concentrations of these metals, these concentrations are also given in the table. It should be noted that except for the limestone liner, the high concentration for a given metal in any given type of liner was not reflected by the low concentrations found in the leachate.

The pH and concentration trends in the test cells are summarized below:

pH: Limestone > control > iron oxide > fly ash
Ni: Iron oxide > limestone > fly ash > control
Zn: Iron oxide > limestone = fly ash > control
Cu: Iron oxide > limestone = fly ash = control
Cr(III): Iron oxide > fly ash > limestone = control
Mn, Pb, and Cd: Limestone > iron oxide = fly ash = control
Fe: Fly ash > control = limestone = iron oxide
Cr(VI): Iron oxide = fly ash = limestone = control

As shown, the iron oxide liner retained more Ni, Zn, Cu, and Cr(III) than the other liners tested; the limestone liner retained more Mn, Pb, and Cd than fly ash or iron oxide. Significant amounts of Fe had leached through and from the iron oxide cells. No differences were detected among the ability of the three liners to retain Cr(IV) (less than 0.2 ug/g in the chemical liners). Of the seven test cells, the lowest metal concentrations were found in the sand layer of the control cell (a blank). This would mean that the three chemical liners had exhibited some ability to retain heavy metals. The data, in general, agree with the findings by Fuller that limestone and hydrous oxides of iron would be potentially useful as chemical liners for retention of metallic leachate constituents (2).

REFERENCES

1. Ponnamperuma, F. N. Dynamic Aspects of Flooded Soils and the Nutrition of the Rice Plants. In: The Mineral Nutrition of the Rice Plant. The Johns Hopkins Press, Baltimore, Maryland, 1965. pp. 295-328.

2. Fuller, W. H. Liners of Natural Porous Materials to Minimize Pollutant Migration. EPA-600/2-81-122, Arizona Agricultural Experiment Station, Tucson, July 1981.

TABLE 15. METAL RETENTION IN THE THREE CHEMICAL LINERS

Liner	pH	Fe	Ni	Zn	Mn	Pb	Cd	Cu	Cr^{+6}	Cr^{+3}	Hg
	mg/kg*										
Control	7.1	237	0.86	0.96	2.06	0.27	0.02	9.75	0.13	2.4	NA#
Limestone	7.9	248	17.2	8.15	97.8	18.1	2.01	12.8	0.17	3.7	0.36
Fly Ash	6.0 (6.8)†	7,442 (6,212)	22.7 (17.4)	31.5 (25.8)	45.4 (100)	15.5 (21.2)	0.42	46.0 (36.3)	0.10	24.8 (8.46)	0.04
Iron Oxide	7.1	195	60.9	37.0	1.84	3.51	0.18	32.0	0.17	42.4	NA

* Concentrations are expressed on an oven-dry weight basis and, except for the control, are averages of two replicate cells.

† Concentrations in fly ash prior to placement into cells. Chromium value is total Cr.

Not analyzed.

3. Artiola, J., and W. H. Fuller. Effect of Crushed Limestone Barriers on Chromium Attenuation in Soils. J. Environ. Qual., 8:503-510, 1979.

SECTION 6

CONCEPTUAL DESIGN AND COST OF A FULL-SCALE DISPOSAL SYSTEM

SITE DESIGN

The design criteria employed here are typical of those used for hazardous waste landfills. Specifically, this disposal system is designed to:

- Contain hazardous contaminants or leachates.
- Comply with federal and/or state regulations for chemical waste landfill facilities.
- Be constructed such that environmental and aesthetic impacts are minimized.
- Be compatible with existing and proposed uses of nearby land.

Site Planning and Design

After a site is selected, an engineering development plan is prepared. This plan generally consists of a report accompanied by drawings and written specifications. Location and design of the waste disposal cell, drainage facilities, access roads, leachate control facilities and other design considerations are included. Results of hydrogeological investigations, procedures to procure site permits, recommendations for equipment purchase, and a description of recommended operational procedures are also integral parts of site planning and design efforts.

For the final design several plan and cross-section drawings would be provided showing intended site features at various phases in the future. Details such as site preparation procedures, the locations of utilities and fences, and fill cell construction methods would be included in the final design. These and other site design considerations are discussed below.

Site Preparation--

A disposal site is generally prepared by clearing shrubs, trees, and other obstacles that would hinder vehicle travel and landfilling operations. Obstructions such as boulders are moved to facilitate construction of buildings, roads, utilities, and drainage structures.

Clearing and grubbing--Trees and brush that hinder landfill equipment or trucks are removed. Brush and tall grass in working areas can be rolled over or grubbed. When possible, natural stands of trees or brush are left in nonworking areas to improve appearance and to control erosion and dust in yet-to-be-filled areas.

Access road--An all-weather access road must be provided from existing arteries to the site. This road should be designed to safely accommodate the anticipated traffic. An access road usually has two lanes of sufficient width and strength to carry the expected delivery vehicles. Access road grades should not exceed 6 to 8 percent. The intersection of the existing public road and the new access road should be designed to reflect traffic volumes and safety requirements.

It is assumed that the on-site access road is approximately 1.6 km (1 mi) and terminates at the delivery control facility. Temporary unpaved roads are used for transporting wastes from this point to the unloading area. Temporary roads are constructed of on-site soil with a topping of suitable material (e.g., gravel, crushed aggregate, cinders, broken concrete, or demolition wastes). Lime, portland cement, or asphalt may be used as a binder to stabilize the roads and to control dust. Asphalt is used at the example site.

Buildings--

Site buildings must be provided to maintain and house equipment used at the site, for office space, and to house appropriate sanitary facilities, a first-aid station, and emergency shower facilities for site employees and users. In the conc ptual design, a single building will serve for equipment maintenance and for office space. (Alternatively, a trailer can be used for office space.) Hypothetical building floor space requirements for the example site are as follows:

- Office - 54 m^2 (600 ft^2).
- Equipment storage/maintenance - 140 m^2 (1560 ft^2).

Utilities--

The chemical waste landfill site must have power, water, and telephone service. Power is required for maintenance of on-site operating equipment and for lighting. Installation of an electrical generator (7-1/2 kW) is planned rather than extension of power lines to the site. Water in sufficient quantities and under adequate pressure is needed in the event of fire, for equipment maintenance, and for dust control; potable water must be made available for site personnel. A 38,000-liter (10,000-gal) elevated storage tank is planned at the site. Water to fill the tank must be periodically hauled to the site and pumped into the tanks. A two-way radio will be provided for communications in place of installing telephone lines to the site.

Fencing--

Fences are used to prevent trespassing by unauthorized persons. A 1.8-m (6-ft) high chain link fence topped with three strands of barbed wire projecting at 45° will be installed around the 8-ha (20-ac) site. The entrance will have an 8-m (26-ft) gate which can be closed and locked when the site is unattended or otherwise closed to users. Signs will be posted, warning that hazardous chemicals are present and unauthorized entry is prohibited.

Drainage Facilities--

Drainage facilities which divert all off-site surface water runoff around the site are required. Also, drainage structures are needed to rapidly divert on-site runoff away from disposal operations. Drainage structure requirements depend on off-site and on-site topographic characteristics, the size of the site, and other factors.

Drainage structures are typically constructed of half-round corrugated metal pipe channels, earth berms and channels, and asphalt concrete-lined channels. The terrain of the site and of the surrounding area suggests that a 76-cm (30-in.) half round metal pipe channel around the site would be adequate to divert off-site surface drainage. Earth berms and channels will be used to control on-site surface waters.

Equipment--

The following equipment will be used at the example disposal site:

- One forklift.
- One front-end loader.
- One track dozer.
- One water truck.
- One pickup truck.

A scraper would be required if it were necessary to haul cover soil long distances (over 100 m, or 330 ft) or if one dozer alone could not efficiently excavate trenches and spread cover soil. For the conceptual design, it is assumed that conditions do not warrant a scraper.

Landfill Construction

Construction of the chemical waste landfill would involve the following steps: cell excavation, installation of a chemical liner and internal leachate collection system, and placement of drainage facilities.

Cell Excavation--

Excavation at the hypothetical site must be such that the disposal cell floors are greater than 15.3 m (50 ft) above maximum ground water elevations, the distance stipulated by EPA regulations. It is assumed that the site meets the ideal conditions.

For illustration, it is further assumed that maximum ground water elevation is 18.3 m (60 ft) below surface grades at the site. Thus, cell excavation can be only 3 m (10 ft) below grade. Additional cell capacity to yield a full depth of 5 m (15 ft) must be provided above grade by constructing berms of compacted soil around the excavation. Figure 23 depicts the disposal cell construction.

Disposal cell plan dimensions will be 200 m x 200 m (650 ft x 650 ft) with side slopes at 2:1 horizontal to vertical. The cell's earth berms will also serve to divert surface runoff away from the disposal area and toward adjacent collection ditches.

Liner Design and Installation--

It is assumed that most soils at the site meet the 10^{-7} cm per sec permeability requirement. A 30-cm (1-ft) layer of chemical liner (limestone, fly ash, or ferric sulfate/sand mixture) will be placed so that it completely covers the bottom and side walls of the cell. The liner will be protected from mechanical damage by covering it with a 30-cm (1-ft) thick layer of compact clayey soil on the side walls and a 30-cm (1-ft) thick layer of sand on the bottom.

Leachate Collection System--

The cell bottom will be graded at a 1 to 2 percent slope, and covered by a 30-cm (1-ft) layer of gravel. A 15-cm (6-in.) layer of sand will be placed on top of the gravel. To sample and collect leachate accumulated in the gravel layer, a leachate collection system will be provided. This system is composed of 200 m (600 ft) of 15-cm (6-in.) perforated vitrified clay pipe situated along the low end of the cell. Access to the collection line is provided by two 12-m (36-ft) leachate standpipes installed against the side wall of the fill. This sloped standpipe design facilitates movement of fill machinery and minimizes the possibility of mechanical damage to the pipes.

COST ESTIMATES

The conceptual design provides a basis for estimating capital and operating cost for the chemical waste landfill.

Cost estimates for the following scenarios are presented in Table 16.

- Landfill lined with limestone.
- Landfill lined with fly ash.
- Landfill lined with ferric sulfate/sand mixture (where ferric sulfate accounts for 5 percent of the liner volume).
- Landfill using native soil liner material (control).

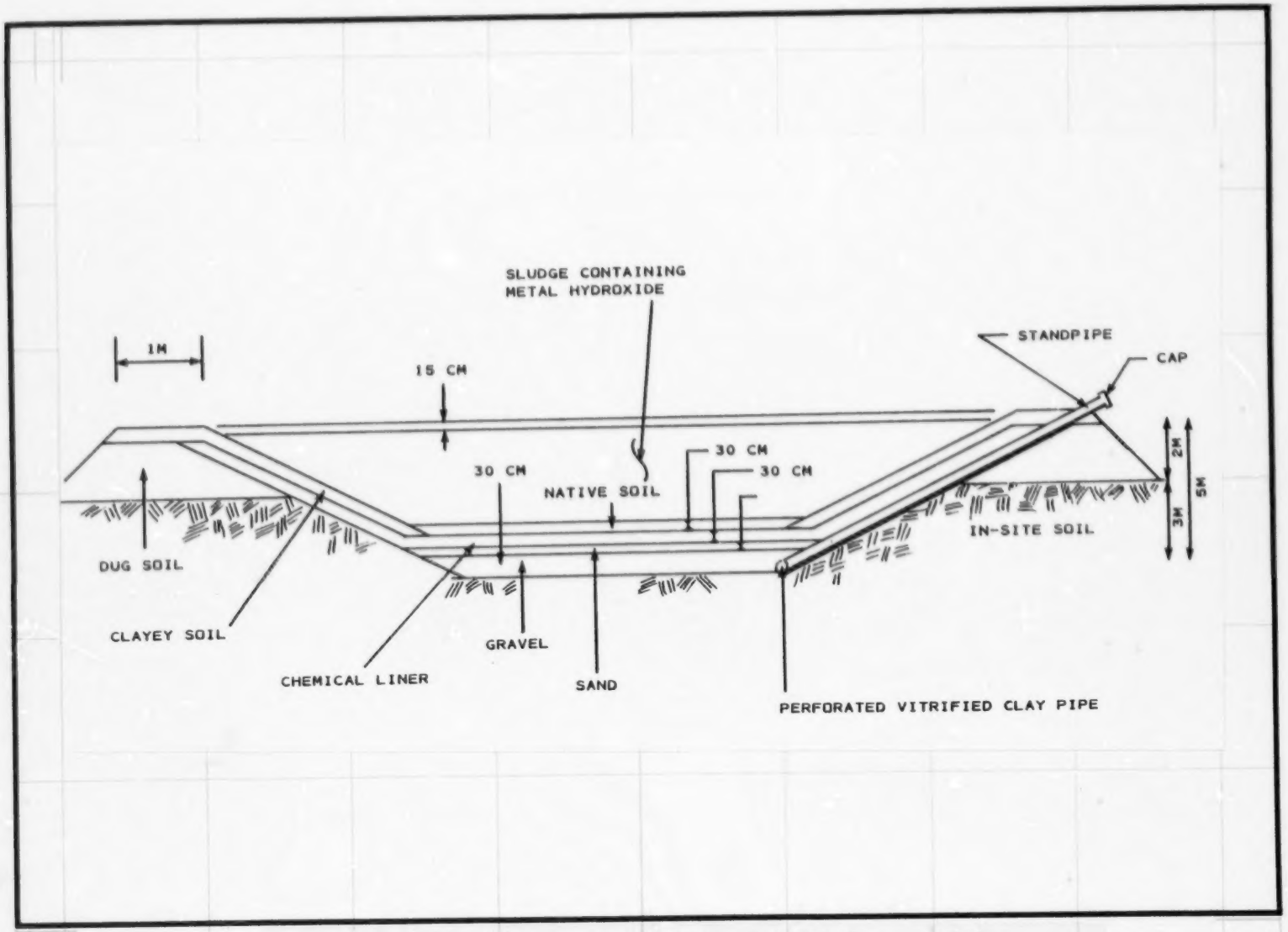

Figure 23. Cell construction detail (no scale).

TABLE 16. CAPITAL COST ESTIMATES FOR CONCEPTUAL SITES USING VARIOUS LINER MATERIALS

	Type of Liner Material Used			
Cost Element	Limestone	Fly Ash	Ferric Sulfate	Control (Native Soil)
Site Construction	$3,767,200	$1,520,800	$28,688,100	$1,474,300
Engineering/Permit	565,100	228,100	4,303,200	221,100
Equipment	220,000	220,000	220,000	220,000
Contingency	910,500	393,800	6,642,300	383,100
Total	5,462,700	2,362,700	39,853,600	2,298,500
Annualized	894,500	389,900	6,491,400	379,500

Differences in liner material costs (Table 17) account for variations in capital costs. Itemized capital costs for a leachate collection system and the landfill using limestone are presented in Tables 18 and 19. Table 20 shows annual O&M costs of each example landfill.

All cost estimates are based on unit construction costs as of mid-1982.

TABLE 17. LINER INSTALLATION COSTS ($)

Cost Element	Type of Liner Material Used			
	Limestone	Fly Ash	Ferric Sulfate	Control (Native Soil)
Material				
- Limestone @ $88/mt	2,288,000*	-	-	-
- Fly Ash (free)	-	0	-	-
- Ferric Sulfate @ $12,000/mt	-	-	26,784,000*	-
- Sand @ $11.52/mt	-	-	424,525*	-
Delivery @ $2.87/m^3	-	41,212	-	-
Installation @ $2.76/m^3	42,193	42,193	42,193	36,921
Total	2,330,193	83,405	27,250,718	36,921
Annualized†	379,228	13,574	4,434,929	6,009

* Delivery cost included.

† Annualized capital recovery (equal annual payment) at 10% interest rate. Recovery period is assumed at 10 years.

TABLE 18. LEACHATE COLLECTION SYSTEM COSTS

Cost Element	Recovery Period (yr)	Unit Cost ($)*	Quantity	Total Cost ($)
Sand	10	11.50/mt	18,000 mt	207,000
Gravel	10	4.50/mt	24,000 mt	108,000
Perforated pipe, 6-in. diameter	10	18.36/m	200 m	3,672
Standpipe, 4-in. diameter	10	21.60/m	24 m	518
Total Cost				319,190
Annualized Cost				51,947†

* Building Construction Cost Data, 1982. R. S. Means Company, Inc., Kingston, Massachusetts.

† Annualized capital recovery (equal annual payment) at 10% interest rate.

TABLE 19. CAPITAL COST ESTIMATES FOR A SLUDGE DISPOSAL SITE USING A LIMESTONE LINER*

Cost Element	Recovery Period (yr)	Unit Cost	Quantity	Total Cost	Annualized Cost†	Ref. for Unit Cost
Clearing and Grubbing	10	$5,247/ha	8 ha	$41,976	$6,831	Means, p. 24
Access Road, Permanent	10	65.50/m	1,615 m	105,800	17,218	EPRI, p. 7.27
Access Road, Temporary	10	20/m	100 m	2,000	325	EPRI, p. 7.27
Drainage structure						
- 30-in 1/2 round CMP	10	69/m	895 m	61,755	10,050	Means, p. 42
- Earth berm	10	2.20/m	895 m	1,969	320	EPRI, p. 7.27
- Debris basin	10	3,000 ea	1	3,000	488	EPRI, p. 7.27
Fencing	10	50/m	1,130 m	56,500	9,195	EPRI, p. 7.27
Building						
- Office	10	448/m^2	54 m^2	24,192	3,937	Means, p. 368
- Maintenance & storage		202/m^2	140 m^2	28,280	4,602	Means, p. 368
Utilities						
- Electric generator	10	4,000 ea	1	4,000	651	EPRI, p. 7.27
- Communication equipment	10	500 ea	1	500	81	EPRI, p. 7.27
- Water tank	10	10,000 ea	1	10,000	1,627	EPRI, p. 7.27
Initial Cell Excavation	10	3.31/m^3	235,000 m^3	777,850	126,592	Means p.29&32
Liner Installation	10	88/mt	26,000 mt	2,330,193	379,228	Means, p. 56

TABLE 19 (continued)

Cost Element	Recovery Period (yr)	Unit Cost	Quantity	Total Cost	Annualized Cost†	Ref. for Unit Cost
Leachate Collection System	10	-	-	$319,190	$51,947	-
Subtotal, Site Construction Costs				3,767,205	-	
Engineering/Permits (15% Site Construction Costs)	10	-	-	565,081	91,964	-
Equipment						
- Fork lift	8	20,000 ea	1	20,000	3,749	EPRI, p. 7.27
- Front-end loader	8	70,000 ea	1	70,000	13,121	EPRI, p. 7.27
- Track dozer	8	100,000 ea	1	100,000	18,744	EPRI, p. 7.27
- Pickup truck	8	10,000 ea	1	10,000	1,874	EPRI, p. 7.27
- Water truck	8	20,000 ea	1	20,000	3,749	EPRI, p. 7.27
Subtotal				4,552,286	-	
Contingencies (20% of Subtotal)	10	-	-	910,457	148,173	-
Total Estimated Capital Costs				5,462,743	-	
Annual Capital Costs †				-	894,466	

* Land procurement excluded.

† Annualized capital recovery (equal annual payments) at 10% interest rate.

TABLE 20. ANNUAL O&M COSTS FOR THE CONCEPTUAL SITE

Cost Element	Unit Cost	Total Units	Annual Cost
Foreman	$20/hr*	2,080	$41,600
Equipment Operator	15/hr*	2,080	31,200
Gatehouse Clerk	7/hr*	2,080	14,560
Equipment Fuel & Maintenance	12/hr	2,080	24,960
Site Utilities			200
Site Security†	20/night	365	7,300
Leachate Monitoring			5,000
Subtotal			124,820
Administrative Costs (15% of Subtotal)			18,723
Annual O&M Cost			143,543

* Fringe benefits included.

† Patrol car drive-by during closed hours.

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

From the results of the field study, the following conclusions can be drawn:

- No significant leaching of heavy metals from the metal hydroxide sludges was observed. The excavated sludges exhibited characteristics similar to the raw sludges originally deposited.

- The pH, soluble salts, and metal concentrations fluctuated to a greater extent in the first 12 to 15 months but leveled off thereafter. The concentrations of various heavy metals in the leachates were not related to their initial concentrations in the sludges.

- The largest volume of leachate was collected from the limestone cells and the smallest volume from the fly ash cells. These volumes were indicative of the permeability variations between chemical liners. There were no direct correlations between amounts of rainfall and leachate volumes.

- Limestone and hydrous oxides of iron appeared to have higher metal retention capacities than did fly ash. However, because of the insignificant leaching of metals from the sludges and the resulting low metal concentrations measured in the chemical liners, the performance of these liners cannot be judged adequately in this study. In addition, the integrity and longevity of the three chemical liners cannot be determined from the laboratory data observations during cell excavation.

- Large quantities of iron were released from the iron oxide cells, resulting in iron enrichment of leachate.

- The costs of the chemical liners account for the differentials in a full-scale landfill operation using these liners. The cost of using hydrous oxides of iron (derived from ferric sulfate) as a chemical liner would be prohibitive.

Additional studies are necessary before the design of a full-scale landfill operation can be realized. These studies should include:

- Arrangement and thickness of the different materials in the cell with respect to maximizing metal retention capacity.
- Leachability of heavy metals from electroplating sludges with lower pH than the materials used in this study.
- Protection for and stability of side slopes that are lined with chemical liners.
- Assessment of the permeabilities of various liner materials under placement (compaction) and chemical conditions.

APPENDIX A

DATA FILE:
LANDFILLING OF METAL HYDROXIDE-CONTAINING SLUDGE

LANDFILLING OF METAL HYDROXIDE - CONTAINING SLUDGES D A T A F I L E JANUARY 1983

****

DATE SAMPLE WAS TAKEN FROM TEST CELL

DECEMBER 14, 1979 SAMPLE #1
JANUARY 20, 1980 SAMPLE #2
FEBRUARY 15, 1980 SAMPLE #3
MARCH 24, 1980 SAMPLE #4
APRIL 24, 1980 SAMPLE #5
MAY 15, 1980 SAMPLE #6
JUNE 13, 1980 SAMPLE #7
JULY 17, 1980 SAMPLE #8
AUGUST 17, 1980 SAMPLE #9
SEPTEMBER 15, 1980 SAMPLE #10
OCTOBER 15,1980 SAMPLE #11
NOVEMBER 15, 1980 SAMPLE #12
DECEMBER 22, 1980 SAMPLE #13
JANUARY 15, 1981 SAMPLE #14
FEBRUARY 19, 1981 SAMPLE #15 - FIRST METALS ANALYSES CONDUCTED BY USC LABORATORY
MARCH 19, 1981 SAMPLE #16 - SAMPLE SET SPLIT WITH COMMERCIAL LABORATORY FOR REPLICATE ANALYSES
APRIL 15, 1981 SAMPLE #17 - SITE RENOVATION CARRIED OUT AFTER SAMPLES WERE COLLECTED
MAY 15, 1981 SAMPLE #18
JUNE 16,1981 SAMPLE #19
JULY 15,1981 SAMPLE #20
AUGUST 14, 1981 SAMPLE #21 - INITIATION OF SAMPLE CONCENTRATION PROCEDURE DURING DIGESTION STEP, TO FACILITATE METALS ANALYSIS

SEPTEMBER 17, 1981 SAMPLE #22
OCTOBER 23, 1981 SAMPLE #23 - CELLS PUMPED DOWN REPEATEDLY IN ATTEMPT TO COMPLETELY DEWATER, OCT.23 THRU 25, 1981
NOVEMBER 13, 1981 SAMPLE #24
DECEMBER 21, 1981 SAMPLE #25 - CELLS PUMPED DOWN AGAIN ON DEC. 22, 1981
JANUARY 6, 1982 SAMPLE #26
FEBRUARY 25, 1982 SAMPLE #27
APRIL 29,1982 SAMPLE #28
JUNE 8,1982 SAMPLE #29 - SMALL AMOUNTS OF SAMPLE #4 AND #7 LOST DURING DIGESTION STEP
JULY 9, 1982 SAMPLE #30 -CELLS PUMPED DOWN REPEATEDLY IN AN ATTEMPT TO COMPLETELY DEWATER, JULY 9 THRU 11,1982
AUGUST 13, 1982 SAMPLE #31 - LAST LEACHATE SAMPLES COLLECTED

****

****
KEY FOR DATA: COLLECTION DATE SAMPLE NUMBER - LETTER CODE DESIGNATING TEST CELL LINER - CELL REPLICATE CODE(A OR B)

C-CONTROL CELL
L-LIMESTONE CELL
F-FLYASH CELL
I-IRON & SAND CELL
A-FIRST CELL AND B-SECOND CELL
****

ANALYTICAL DATA FOR THE CELLS -- ALL VALUES ARE IN mg/l,EXCEPT pH. CONDUCTIVITY (COND) IS EXPRESSED IN MICROMHOS/CENTIMETER AT STATED TEMP. IN DEGREES C

****

ID	pH	Cn	Cr+6	Cr+3	Cd	Cu	Fe	Mn	Ni	Pb	Zn	B	Se	H2O DEPTH [CM]	H2O VOL [L] 1 ST	& TOTAL	COND/TEMP
1CA	4.2	0.04	74.0	25.0	<0.01	0.16	0.55	0.73	0.80	0.51	0.02	-	-	-	-	-	-

2CA	5.3	<0.01	11.7	4.9	0.02	0.14	0.34	0.43	0.64	0.46	0.20	-	-	-	-	-	-
3CA	6.0	N/A	0.96	0.95	0.03	0.10	1.44	0.67	0.57	0.14	0.10	-	-	-	-	-	-
4CA	7.0	N/A	<0.05	0.44	0.06	0.09	6.30	1.50	0.58	0.23	0.17	-	-	-	-	-	-
5CA	7.3	N/A	<0.05	0.21	0.05	0.37	9.80	0.58	1.60	0.14	0.42	-	-	-	-	-	-
6CA	7.0	N/A	<0.02	0.25	0.04	0.06	26.80	2.30	0.48	0.09	0.35	-	-	-	-	-	-
7CA	6.2	N/A	<0.02	0.22	0.06	0.52	39.40	2.70	0.55	0.18	0.21	-	-	-	-	-	-
8CA	7.9	N/A	<0.02	0.12	0.05	0.36	13.00	1.90	0.51	0.15	0.16	-	-	-	-	-	-
9CA	7.3	N/A	<0.02	0.20	<0.01	0.26	17.60	2.80	0.55	0.18	0.35	-	-	-	-	-	-
10CA	5.7	N/A	<0.02	0.02	0.03	0.52	16.60	1.40	0.46	0.07	0.18	-	-	-	-	-	-
11CA	5.7	N/A	<0.02	0.21	<0.01	0.20	11.80	1.44	0.45	0.01	0.14	-	-	-	-	-	-
12CA	7.2	N/A	<0.02	0.11	0.03	0.15	13.70	1.19	0.47	0.04	0.17	-	-	-	-	-	-
13CA	7.2	N/A	<0.02	<0.01	0.01	0.06	11.20	2.70	<0.01	0.06	0.06	-	-	143.5	62	-	-
14CA	6.1	N/A	<0.02	<0.01	0.03	0.16	21.20	0.18	0.34	0.09	0.15	3.2	<1.0	172.7	91	-	-
15CA	5.1	N/A	<0.02	<0.01	0.02	0.10	10.14	1.15	0.23	0.17	0.04	5.5	11.0	205.7	86	-	4700/23
16CA	5.7	N/A	<0.02	0.04	0.03	0.06	10.4	1.11	0.23	0.15	<.01	5.4	2.1	193.0	85	-	3200/23
17CA	6.0	N/A	<0.02	0.06	0.03	0.05	16.84	1.04	0.23	0.13	0.15	6.2	12.1	167.6	68	-	5800/23
18CA	6.0	N/A	<0.02	0.03	0.01	0.03	16.22	0.97	0.24	0.09	0.01	4.4	4.2	166.3	133	-	5800/23
19CA	6.3	N/A	<0.02	0.04	0.01	0.04	14.41	1.34	0.25	0.05	0.16	7.4	21.0	172.7	80	-	4900/24
20CA	6.4	N/A	<0.02	0.04	0.01	0.05	13.81	0.78	0.31	0.04	0.16	5.1	23.0	184.1	175	-	4800/25
21CA	5.9	N/A	<0.02	<.01	<0.01	0.16	10.09	0.60	0.19	0.03	0.36	5.0	18.0	193.0	86	-	4600/24
22CA	6.1	N/A	<0.02	0.01	<0.01	0.11	9.46	0.69	0.23	0.05	0.10	5.4		156.2	76	-	4300/24
23CA	6.0	N/A	<0.02	<.01	<0.01	0.05	7.59	0.47	0.19	0.02	0.06	5.2		113.0	301	710	3700/24
24CA	5.8	N/A	<0.02	0.04	<0.01	0.06	7.97	0.13	0.13	0.02	0.08	4.8		43.1	284	-	3000/23
25CA	5.6	N/A	<0.02	0.08	<0.01	0.46	7.16	0.29	0.18	0.03	0.22	6.0		55.8	265	265	2800/19
26CA	5.5	N/A	<0.02	0.01	<0.01	0.03	5.40	0.24	0.13	0.01	0.08	6.1		196.0	102	178	2400/22
27CA	6.4	N/A	<0.02	0.01	0.01	0.36	11.29	0.29	0.11	0.02	0.15	4.8		176.5	117	-	3500/24
28CA	5.9	N/A	<0.02	0.14	<0.01	0.09	10.30	0.58	0.15	0.04	0.08	5.9		181.5	161	-	3700/23
29CA	5.5	N/A	<0.02	0.06	0.01	0.09	7.68	0.40	0.14	0.05	0.30	5.0		183.0	128	494	3500/24
30CA	5.9	N/A	<0.02	<.01	<0.01	0.03	4.29	0.26	0.08	0.01	0.03	5.8		131.0	128	676	2600/22
31CA	5.5	N/A	<0.02	0.02	<0.01	0.01	0.94	0.18	0.09	0.04	0.04	5.9		184.0	98	140	2700/22

ID	pH	Cn	Cr+6	Cr+3	Cd	Cu	Fe	Mn	Ni	Pb	Zn	B	Se	H2O DEPTH [CM]	H2O VOL 1 ST	H2O VOL %	ELJ TOTAL	COND/TEMP
1LA	3.5	0.06	100.00	61.00	<0.01	0.15	0.37	0.46	1.30	0.63	0.03	-	-	-	-		-	-
2LA	4.2	0.04	70.00	6.00	0.02	0.34	0.25	0.30	0.91	0.50	0.15	-	-	-	-		-	-
3LA	6.0	N/A	39.0	3.0	0.03	0.11	0.78	0.33	0.72	0.16	0.23	-	-	-	-		-	-
4LA	7.3	N/A	14.0	18.20	0.03	0.10	0.33	0.26	0.57	0.26	0.13	-	-	-	-		-	-
5LA	7.8	N/A	3.00	1.50	0.01	0.18	0.61	0.49	0.28	0.16	0.73	-	-	-	-		-	-
6LA	7.7	N/A	0.13	2.00	0.03	0.08	4.80	0.43	0.45	0.12	0.06	-	-	-	-		-	-
7LA	6.2	N/A	<0.02	0.28	0.05	0.17	6.80	0.60	0.49	0.07	0.08	-	-	-	-		-	-
8LA	7.2	N/A	<0.02	0.17	0.04	0.08	4.90	0.70	0.39	0.08	0.09	-	-	-	-		-	-
9LA	7.6	N/A	<0.02	0.03	<0.01	0.04	6.60	1.10	0.38	0.10	0.20	-	-	-	-		-	-
10LA	5.8	N/A	<0.02	<0.01	0.02	0.09	6.50	0.80	0.30	<0.01	0.07	-	-	-	-		-	-
11LA	7.2	N/A	<0.02	0.07	<0.01	0.06	5.80	1.03	0.37	<0.01	0.20	-	-	-	-		-	-
12LA	7.0	N/A	<0.02	<0.01	<0.01	0.05	6.30	0.81	0.36	0.01	0.10	-	-	138.9	175		-	-
13LA	6.0	N/A	<0.02	<0.01	0.01	0.02	7.20	1.50	<0.01	0.07	0.01	-	-	147.3	175		-	-
14LA	7.1	N/A	<0.02	<0.01	0.02	<0.01	13.90	1.38	0.20	0.08	0.04	2.9	<1.0	193.0	80		-	3900/23
15LA	5.8	N/A	<0.02	0.04	0.05	0.04	3.85	0.49	0.13	0.08	0.73	5.1	5.5	187.9	205		-	3100/23
16LA	5.7	N/A	<0.02	<0.01	0.02	0.03	4.00	0.49	0.11	0.12	0.01	3.9	4.7	137.1	420		-	3200/23
17LA	6.0	N/A	<0.02	0.04	0.02	<.01	5.48	0.38	0.13	0.05	<.01	4.6	6.8	81.2	305		-	2700/23
18LA	6.1	N/A	<0.02	0.03	<.01	0.08	3.48	0.29	0.09	0.06	0.05	3.8	3.3	154.9	427		-	2300/24
19LA	6.0	N/A	<0.02	0.02	<.01	0.03	1.99	0.19	0.11	0.06	<.01	4.0	10.0	170.1	550		-	2300/25
20LA	5.8	N/A	<0.02	<.01	<.01	0.01	0.95	0.16	0.11	0.04	<.01	5.1	23.0	179.7	462		-	2300/24
21LA	5.8	N/A	<0.02	<.01	<.01	0.01	0.49	0.17	0.01	0.01	0.02	5.2	26.0	149.6	442		-	2100/24
22LA	5.9	N/A	<0.02	<.01	<.01	0.04	1.11	0.17	0.14	0.03	0.02	6.0		60.9	231		380	2000/24
23LA	5.9	N/A	<0.02	<.01	<.01	0.01	0.78	0.16	0.09	<.01	0.05	5.9		40.6	136		-	1700/23
24LA	5.5	N/A	<0.02	<.01	<.01	0.05	0.28	0.09	0.08	<.01	0.03	4.9		119.3	424		424	1900/19
25LA	5.5	N/A	<0.02	<.01	0.03	0.05	2.84	0.13	0.07	<.01	1.34	5.6		183.5	386		386	1500/22
26LA	5.5	N/A	<0.02	0.02	<.01	0.03	5.40	0.24	0.13	0.01	0.08	5.9		156.8	413		-	1800/24
27LA	6.3	N/A	<0.02	<.01	<.01	0.02	0.34	0.10	0.08	<.01	0.03	5.8		174.0	483		-	1700/23
28LA	5.8	N/A	<0.02	0.01	<.01	0.02	0.58	1.20	0.08	0.01	0.02	5.0						

29LA	6.0	N/A	<0.02	0.04	<.01	0.03	1.71	0.09	0.06	0.03	0.05	5.7	145.0	434	-	1500/24
30LA	5.7	N/A	<0.02	<.01	<.01	0.02	0.07	0.06	0.03	0.02	0.03	5.7	144.0	381	600	1200/23
31LA	5.5	N/A	<0.02	<0.01	<.01	0.05	0.17	0.06	0.05	0.03	0.10	5.5	183.0	386	594	1400/22

ID	pH	Cn	Cr+6	Cr+3	Cd	Cu	Fe	Mn	Ni	Pb	Zn	B	Se	H2O DEPTH [CM]	H2O VOL 1 ST	H2O VOL % TOTAL	COND/TEMP
1LB	4.2	0.76	99.00	39.00	<0.01	0.14	0.42	0.34	1.10	0.06	0.01	-	-	-	-	-	-
2LB	5.5	0.41	69.00	15.00	0.02	0.17	0.65	0.31	0.94	0.56	0.13	-	-	-	-	-	-
3LB	6.0	N/A	52.00	8.70	0.04	0.13	0.38	0.38	0.83	0.19	0.17	-	-	-	-	-	-
4LB	8.1	N/A	28.00	30.20	0.05	0.13	0.51	0.31	0.79	0.31	0.16	-	-	-	-	-	-
5LB	7.8	N/A	9.40	2.60	0.01	0.14	0.42	0.86	0.34	0.14	0.38	-	-	-	-	-	-
6LB	7.0	N/A	<0.02	0.91	0.05	0.04	8.70	0.58	0.71	0.14	0.39	-	-	-	-	-	-
7LB	6.1	N/A	<0.02	0.31	0.06	<0.01	11.70	0.72	0.60	0.10	0.21	-	-	-	-	-	-
8LB	6.3	N/A	<0.02	0.25	0.06	0.08	6.40	0.93	0.57	0.13	0.09	-	-	-	-	-	-
9LB	6.5	N/A	<0.02	0.17	<0.01	0.04	7.00	1.00	0.44	0.12	0.11	-	-	-	-	-	-
10LB	7.7	N/A	<0.02	0.02	0.03	0.06	8.00	0.70	0.37	0.02	0.07	-	-	-	-	-	-
11LB	5.9	N/A	<0.02	0.19	<0.01	0.02	2.17	0.65	0.35	<0.01	0.08	-	-	-	-	-	-
12LB	7.1	N/A	<0.03	0.04	<0.01	0.01	1.44	0.47	0.31	<0.01	0.08	-	-	97.1	398	-	-
13LB	8.1	N/A	<0.02	<0.01	0.01	0.09	2.40	0.90	0.26	0.10	0.04	-	-	111.8	340	-	-
14LB	5.6	N/A	<0.02	<0.01	0.03	<0.01	1.70	0.83	0.13	0.13	0.07	2.1	<1.0	202.2	340	-	3500/23
15LB	5.5	N/A	<0.02	0.07	0.03	0.04	2.57	0.26	0.09	0.10	0.29	3.7	6.7	136.1	65	-	3200/23
16LB	5.6	N/A	<0.02	0.05	0.02	0.03	4.39	0.44	0.08	0.14	<.01	3.7	2.2	142.5	461	-	2800/23
17LB	6.0	N/A	<0.02	0.02	0.02	<0.01	1.85	0.34	0.06	0.09	<.01	4.1	8.3	85.3	305	-	2700/23
18LB	6.0	N/A	<0.02	<.01	0.01	0.02	2.19	0.26	0.03	0.06	<.01	4.6	3.3	156.4	443	-	2200/24
19LB	6.1	N/A	<0.02	0.02	<.01	0.03	0.30	0.15	0.07	0.07	0.07	3.3	5.0	175.5	491	-	2100/25
20LB	5.9	N/A	<0.02	0.06	<.01	0.04	1.18	0.16	0.07	0.05	0.02	4.3	6.0	186.3	516	-	2100/24
21LB	5.9	N/A	<0.02	<.01	<.01	<.01	0.67	0.18	0.06	<.01	0.12	4.4	16.0	148.0	460	-	1700/24
22LB	6.0	N/A	<0.02	<.01	<.01	0.06	0.85	0.20	0.09	0.04	<.01	4.8		63.7	240	366	1800/24
23LB	5.9	N/A	<0.02	<.01	<.01	0.01	0.78	0.16	0.09	<.01	0.05	4.8		34.5	129	-	1500/23
24LB	5.5	N/A	<0.02	<.01	<.01	0.03	0.39	0.07	0.09	0.01	0.02	4.0		134.9	481	481	1800/19
25LB	5.2	N/A	<0.02	0.08	<.01	0.10	0.62	0.08	0.06	<.01	0.04	4.9		189.0	515	615	1400/22
26LB	5.5	N/A	<0.02	0.06	<.01	0.05	0.63	0.05	0.10	0.04	0.05	4.8		167.9	492	-	1700/24
27LB	6.3	N/A	<0.02	<.01	<.01	0.02	0.22	0.04	0.06	0.02	0.02	4.7		184.0	515	-	1500/23
28LB	5.8	N/A	<0.02	0.03	<.01	2.07	3.63	2.03	0.10	0.13	1.01	4.3		174.0	498	-	1600/24
29LB	5.5	N/A	<0.02	0.09	<.01	0.02	1.80	0.16	0.07	0.02	0.03	4.8		155.0	438	709	1300/22
30LB	5.7	N/A	<0.02	<.01	<.01	0.02	0.42	0.11	0.05	0.01	0.13	4.1		191.0	492	500	1400/22
31LB	5.3	N/A	<0.02	0.01	<.01	0.04	0.17	0.06	0.05	0.02	0.05	4.8					

ID	pH	Cn	Cr+6	Cr+3	Cd	Cu	Fe	Mn	Ni	Pb	Zn	B	Se	H2O DEPTH [CM]	H2O VOL 1 ST	H2O VOL % TOTAL	COND/TEMP
1FA	7.5	0.02	27.00	16.00	0.04	0.4	12.00	0.86	0.78	0.66	0.24	-	-	-	-	-	-
2FA	7.1	0.03	2.53	4.62	0.03	0.31	3.90	0.75	0.72	0.66	0.08	-	-	-	-	-	-
3FA	6.0	N/A	<0.02	0.65	0.05	0.29	14.40	2.60	0.69	0.22	0.20	-	-	-	-	-	-
4FA	7.6	N/A	0.10	0.45	0.06	0.23	12.10	1.90	0.64	0.32	0.12	-	-	-	-	-	-
5FA	7.6	N/A	<0.05	0.18	0.01	0.22	15.60	0.70	1.60	0.04	0.30	-	-	-	-	-	-
6FA	7.8	N/A	<0.02	0.31	0.06	0.12	18.40	1.80	0.58	0.11	0.09	-	-	-	-	-	-
7FA	6.3	N/A	<0.02	0.10	0.07	0.13	9.80	2.40	0.61	0.13	0.11	-	-	-	-	-	-
8FA	6.6	N/A	<0.02	0.14	0.06	0.14	3.60	1.[illegible]	0.54	0.13	0.13	-	-	-	-	-	-
9FA	6.4	N/A	<0.02	0.12	0.02	0.30	4.80	1.00	0.48	0.19	0.14	-	-	-	-	-	-
10FA	6.5	N/A	<0.02	0.06	0.04	0.16	2.34	0.72	0.48	0.01	0.16	-	-	-	-	-	-
11FA	6.3	N/A	<0.02	0.12	0.02	0.21	2.25	0.82	0.50	0.04	0.08	-	-	-	-	-	-
12FA	6.9	N/A	<0.02	0.08	0.02	0.11	3.40	0.79	0.53	0.05	0.10	-	-	-	-	-	-
13FA	7.6	N/A	<0.02	<0.01	0.02	0.04	5.60	2.00	0.44	0.07	0.06	-	-	148.8	21	-	-
14FA	6.5	N/A	<0.02	0.04	0.05	0.04	7.80	3.60	0.50	0.23	0.07	2.9	3.5	152.4	21	-	-
15FA	6.0	N/A	<0.02	0.08	0.03	0.15	2.27	1.33	0.24	0.18	0.43	4.3	10.5	188.0	30	-	10200/23

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16FA	6.1	N/A	<0.02	0.03	0.03	0.05	3.18	1.99	0.21	0.15	0.15	3.2	<10.0	170.2	60	-	8800/23
17FA	6.4	N/A	<0.02	0.05	0.02	0.03	3.48	2.15	0.20	0.14	<.01	4.5	17.0	144.8	20	-	9100/23
18FA	6.4	N/A	<0.02	0.06	0.01	0.04	6.27	2.44	0.22	0.10	<.01	3.8	19.0	146.1	20	-	9000/23
19FA	6.5	N/A	<0.02	0.03	0.01	0.03	6.81	2.49	0.21	0.13	0.12	5.9	30.0	144.8	20	-	7800/24
20FA	6.1	N/A	<0.02	0.04	0.01	0.03	6.81	2.99	0.24	0.10	0.01	4.3	33.0	160.8	27	-	8000/25
21FA	6.2	N/A	<0.02	<.01	<.01	0.01	9.36	4.01	0.23	0.05	0.06	4.2	36.0	172.8	35	-	8300/24
22FA	6.3	N/A	<0.02	0.02	0.01	0.21	8.29	4.98	0.23	0.08	0.17	5.2		135.5	32	-	7500/24
23FA	6.2	N/A	<0.02	<.01	<.01	0.01	10.99	3.69	0.19	0.03	0.06	5.0		96.6	15	70	7900/24
24FA	6.0	N/A	<0.02	<.01	<.01	0.02	11.56	5.87	0.19	0.03	0.01	4.4		124.5	19	-	6900/23
25FA	5.7	N/A	<0.02	<.01	<.01	<.01	10.40	5.94	0.17	<.01	0.02	5.0		162.6	30	40	7100/19
26FA	5.7	N/A	<0.02	0.03	<.01	0.02	8.67	5.95	0.18	0.03	0.03	5.0		177.0	28	57	6300/22
27FA	6.3	N/A	<0.02	0.02	0.01	0.02	19.04	5.75	0.15	0.04	0.02	5.0		151.2	27	-	8200/24
28FA	5.8	N/A	<0.02	0.47	0.01	0.22	35.59	6.19	0.41	0.08	1.21	4.6		166.5	34	-	8800/23
29FA	5.9	N/A	<0.02	0.21	0.01	0.09	26.17	4.93	0.19	0.08	0.08	5.1		158.0	30	-	8700/24
30FA	6.3	N/A	<0.02	0.01	<.01	0.03	12.55	5.00	0.18	0.02	0.07	5.2		143.0	23	115	7200/22
31FA	5.6	N/A	<0.02	0.03	<.01	0.02	12.08	3.90	0.17	0.03	0.17	4.5		173.0	26	55	7200/22

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ID	pH	Cn	Cr+6	Cr+3	Cd	Cu	Fe	Mn	Ni	Pb	Zn	B	Se	H2O DEPTH [CM]	H2O VOL 1 ST	[L] & TOTAL	COND/TEMP
1FB	9.2	4.90	<0.02	0.31	0.03	0.27	3.80	0.42	0.30	0.60	0.04	-	-	-	-	-	-
2FB	8.5	1.90	<0.02	0.23	0.02	0.57	22.00	0.48	0.45	0.59	0.20	-	-	-	-	-	-
3FB	6.8	N/A	<0.02	0.10	0.04	0.26	1.62	0.47	0.23	0.17	0.16	-	-	-	-	-	-
4FB	8.0	N/A	<0.05	0.15	0.05	0.34	0.95	0.46	0.17	0.26	0.15	-	-	-	-	-	-
5FB	7.5	N/A	<0.05	0.13	0.02	0.28	1.27	0.17	0.37	0.14	0.31	-	-	-	-	-	-
6FB	8.1	N/A	<0.02	0.42	0.04	0.74	1.71	0.42	0.23	0.09	0.08	-	-	-	-	-	-
7FB	7.0	N/A	<0.02	0.15	0.06	0.43	5.40	0.43	0.20	0.09	0.09	-	-	-	-	-	-
8FB	7.9	N/A	<0.02	0.14	0.05	0.45	0.46	0.36	0.18	0.10	0.11	-	-	-	-	-	-
9FB	7.2	N/A	<0.02	0.13	0.01	0.30	0.74	0.50	0.18	0.13	0.15	-	-	-	-	-	-
10FB	8.0	N/A	<0.02	0.02	0.04	0.67	0.91	0.31	0.17	0.05	0.18	-	-	-	-	-	-
11FB	6.7	N/A	<0.02	0.33	0.02	1.02	26.00	0.57	0.33	0.39	0.24	-	-	-	-	-	-
12FB	7.0	N/A	<0.02	0.16	0.02	0.61	10.20	0.43	0.32	0.09	0.23	-	-	-	-	-	-
13FB	8.0	N/A	<0.02	0.02	0.02	0.39	2.70	1.00	0.29	0.12	0.09	-	-	163.8	20	-	-
14FB	6.5	N/A	<0.02	0.08	0.05	0.46	12.60	1.21	0.17	0.26	0.12	3.2	46.8	165.1	20	-	-
15FB	6.3	N/A	<0.02	0.09	0.03	0.37	3.86	0.42	0.07	0.18	0.23	5.9	29.0	198.2	23	-	12200/23
16FB	6.3	N/A	<0.02	0.07	0.03	0.15	2.95	0.51	0.08	0.17	0.08	3.5	37.0	182.9	20	-	10600/23
17FB	6.6	N/A	<0.02	0.09	0.02	0.13	2.53	0.51	0.05	0.12	<.01	5.5	46.0	158.8	20	-	10500/23
18FB	6.6	N/A	<0.02	<.01	0.01	0.18	3.44	0.54	0.13	0.18	0.14	4.5	49.0	165.1	18	-	11600/23
19FB	6.7	N/A	<0.02	0.07	0.01	0.46	6.77	0.52	0.17	0.16	0.07	5.9	25.0	160.1	22	-	9900/24
20FB	6.4	N/A	<0.02	0.04	0.01	0.20	2.35	0.52	0.17	0.12	0.09	6.0	33.0	175.9	24	-	10200/25
21FB	6.6	N/A	<0.02	0.02	<.01	0.13	5.06	0.55	0.15	0.04	0.11	5.2	53.0	185.1	21	-	10000/24
22FB	6.7	N/A	<0.02	0.01	0.01	0.31	2.79	0.53	0.16	0.09	0.06	5.9		152.5	18	-	8800/24
23FB	6.4	N/A	<0.02	0.01	<.01	0.05	2.17	0.11	0.09	0.02	0.05	4.2		115.6	19	61	9200/24
24FB	6.3	N/A	<0.02	<.01	<.01	0.02	11.56	5.87	0.19	0.03	0.01	5.1		147.4	19	-	8400/23
25FB	6.1	N/A	<0.02	<.01	0.11	0.19	9.74	0.76	0.13	0.02	0.30	6.3		177.8	25	46	7900/19
26FB	6.0	N/A	<0.02	0.02	0.01	0.09	2.20	0.84	0.15	0.04	0.03	6.1		189.0	27	45	6600/22
27FB	6.1	N/A	<0.02	0.06	0.01	0.28	18.69	0.90	0.13	0.03	0.04	5.9		165.0	27	-	9300/24
28FB	6.1	N/A	<0.02	0.07	0.01	0.46	2.21	1.11	0.35	0.08	0.08	5.0		180.5	31	-	10000/23
29FB	6.2	N/A	<0.02	0.45	0.01	0.77	74.75	1.37	0.32	0.17	0.42	7.8		174.0	26	-	9700/24
30FB	6.4	N/A	<0.02	0.01	<.01	0.10	2.48	0.96	0.16	0.03	0.06	6.5		166.0	26	64	8500/22
31FB	6.6	N/A	<0.02	0.05	<.01	0.21	2.33	0.78	0.18	0.05	0.13	5.3		184.0	45	74	8400/22

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ID	pH	Cn	Cr+6	Cr+3	Cd	Cu	Fe	Mn	Ni	Pb	Zn	B	Se	H2O DEPTH [CM]	H2O VOL 1 ST	[L] & TOTAL	COND/TEMP
1IA	4.8	<0.01	<0.02	2.60	0.06	0.26	87.00	12.60	0.79	0.73	2.07	-	-	-	-	-	-
2IA	4.6	<0.01	<0.02	0.04	0.04	0.29	65.00	11.50	1.01	0.68	2.19	-	-	-	-	-	-

3IA	4.5	N/A	<0.02	0.04	0.06	0.28	30.40	10.60	0.96	0.25	2.20	-	-	-	-	-	-
4IA	4.8	N/A	<0.05	1.26	0.06	0.23	16.90	7.30	1.03	0.34	1.89	-	-	-	-	-	-
5IA	4.6	N/A	<0.05	0.55	0.05	0.25	22.80	0.94	9.80	0.61	0.40	-	-	-	-	-	-
6IA	5.0	N/A	<0.02	0.91	0.06	0.22	48.60	6.30	1.07	0.15	1.79	-	-	-	-	-	-
7IA	5.0	N/A	<0.02	0.13	0.07	0.21	28.40	3.60	0.86	0.12	0.90	-	-	-	-	-	-
8IA	5.7	N/A	<0.02	0.08	0.06	0.17	4.50	4.30	0.72	0.15	0.53	-	-	-	-	-	-
9IA	5.5	N/A	<0.02	0.04	0.01	0.05	173.0	4.40	0.39	0.15	0.17	-	-	-	-	-	-
10IA	5.5	N/A	<0.02	<0.01	0.04	0.06	410.0	2.90	0.26	0.04	0.01	-	-	-	-	-	-
11IA	5.7	N/A	<0.02	0.09	0.02	0.04	187.0	3.10	0.29	<0.01	0.10	-	-	-	-	-	-
12IA	6.7	N/A	<0.02	0.03	0.02	0.10	163.0	2.90	0.32	0.01	0.11	-	-	-	-	-	-
13IA	6.2	N/A	<0.02	0.02	0.02	0.07	540.0	7.30	0.26	<0.01	0.07	-	-	165.6	52	-	-
14IA	5.9	N/A	<0.02	0.01	0.04	0.04	138.0	4.80	0.17	0.12	0.07	3.2	6.2	167.6	48	-	-
15IA	6.0	N/A	<0.02	0.07	0.03	0.10	66.74	1.75	0.07	0.14	0.22	4.5	18.0	210.9	51	-	8300/23
16IA	6.0	N/A	<0.02	0.04	0.03	0.03	70.0	1.51	0.08	0.13	0.05	2.7	1.2	190.5	61	-	7200/23
17IA	6.5	N/A	<0.02	0.02	0.02	0.03	69.36	1.34	0.08	0.09	<.01	4.5	12.0	158.8	33	-	7100/23
18IA	6.2	N/A	<0.02	<.01	0.01	0.02	58.60	1.10	0.08	<0.01	<.01	3.7	4.4	169.0	77	-	7600/23
19IA	6.5	N/A	<0.02	<.01	0.01	0.03	45.78	0.84	0.11	0.13	0.14	5.3	25.0	165.1	91	-	6500/24
20IA	6.1	N/A	<0.02	<.01	0.01	0.03	24.88	0.22	0.13	0.08	0.12	4.3	28.0	178.5	348	-	6200/25
21IA	6.3	N/A	<0.02	<.01	<.01	<.01	9.70	0.34	0.13	0.03	0.02	4.6	26.0	190.5	325	-	6100/24
22IA	6.4	N/A	<0.02	<.01	<.01	0.05	8.34	0.26	0.14	0.06	0.04	5.2		159.0	324	-	5100/24
23IA	6.1	N/A	<0.02	<.01	0.01	0.04	8.89	0.04	0.11	0.03	0.07	4.8		73.7	197	376	5400/24
24IA	6.4	N/A	<0.02	<.01	0.01	0.12	15.20	0.02	0.11	0.03	0.03	4.8		81.3	140	-	4600/23
25IA	5.7	N/A	<0.02	<.01	0.12	0.05	11.97	0.21	0.08	<.01	0.04	5.4		185.5	95	141	4900/19
26IA	5.9	N/A	<0.02	<.01	<.01	0.02	5.10	0.13	0.09	0.04	0.01	4.2		198.0	57	95	4300/22
27IA	5.0	N/A	<0.02	0.02	<.01	0.06	6.54	0.14	0.08	0.02	0.02	4.7		167.7	47	-	4900/24
28IA	6.3	N/A	<0.02	0.81	0.01	9.90	23.49	1.55	0.56	1.31	6.41	5.9		186.5	182	-	5900/23
29IA	6.3	N/A	<0.02	0.15	0.01	0.04	12.05	0.14	0.09	0.07	0.04	5.3		178.0	72	-	5600/24
30IA	5.8	N/A	<0.02	0.02	<.01	0.04	2.86	0.08	0.09	0.02	0.11	4.8		165.0	34	293	4600/22
31IA	6.2	N/A	<0.02	0.04	<.01	0.05	3.47	0.08	0.10	0.02	0.11	4.5		192.0	47	100	4300/22

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ID	pH	Cn	Cr+6	Cr+3	Cd	Cu	Fe	Mn	Ni	Pb	Zn	B	Se	H2O DEPTH [CM]	H2O VOL 1 ST	% [L] TOTAL	COND/TEMP
1IB	7.0	0.36	<0.02	1.32	0.03	0.81	42.00	0.44	0.99	0.28	0.63	-	-	-	-	-	-
2IB	7.0	<0.01	<0.02	0.04	0.02	0.10	44.00	0.54	0.30	0.33	0.06	-	-	-	-	-	-
3IB	6.5	N/A	<0.02	0.04	0.02	0.09	16.40	0.64	0.30	0.09	0.16	-	-	-	-	-	-
4IB	7.5	N/A	<0.05	0.31	0.03	0.11	11.80	0.47	0.46	0.16	0.14	-	-	-	-	-	-
5IB	7.6	N/A	<0.05	0.17	0.01	0.14	8.80	0.40	0.42	0.12	0.22	-	-	-	-	-	-
6IB	7.7	N/A	<0.02	0.36	0.03	0.25	20.00	0.43	0.45	0.03	0.10	-	-	-	-	-	-
7IB	6.5	N/A	<0.02	0.37	0.05	0.35	17.00	0.47	0.66	0.04	0.28	-	-	-	-	-	-
8IB	6.5	N/A	<0.02	0.33	0.04	0.22	69.30	0.30	0.57	0.06	0.15	-	-	-	-	-	-
9IB	6.3	N/A	<0.02	0.13	<0.01	0.08	9.30	0.46	0.38	0.07	0.20	-	-	-	-	-	-
10IB	6.6	N/A	<0.02	0.11	0.03	0.29	8.00	0.39	0.39	0.08	0.24	-	-	-	-	-	-
11IB	6.5	N/A	<0.02	1.03	<0.01	0.37	8.20	0.39	1.06	<0.01	0.45	-	-	-	-	-	-
12IB	6.9	N/A	<0.02	0.60	0.01	0.17	8.30	0.45	0.82	<0.01	0.30	-	-	-	-	-	-
13IB	7.7	N/A	<0.02	0.31	0.01	0.46	7.90	1.00	0.69	<0.01	0.25	-	-	174.8	42	-	-
14IB	6.5	N/A	<0.02	0.15	0.03	0.07	15.90	1.09	0.47	0.10	0.10	0.7	2.1	177.8	40	-	-
15IB	6.3	N/A	<0.02	0.12	0.02	0.14	5.04	0.38	0.23	0.08	<.01	4.4	8.8	215.9	44	-	8300/23
16IB	6.2	N/A	<0.02	0.03	0.02	0.04	6.10	0.46	0.16	0.12	<.01	2.7	1.2	196.5	45	-	6000/23
17IB	6.7	N/A	<0.02	0.05	0.02	0.05	11.74	0.49	0.15	0.07	0.05	4.5	13.0	166.4	30	-	7000/23
18IB	6.8	N/A	<0.02	<.01	0.01	0.07	12.79	0.46	0.19	0.08	0.03	3.9	18.0	177.8	35	-	6800/23
19IB	7.1	N/A	<0.02	0.05	0.01	0.05	11.55	0.45	0.19	0.09	0.80	4.7	26.0	177.8	31	-	6000/24
20IB	6.5	N/A	<0.02	0.04	0.01	0.04	10.26	0.44	0.19	0.05	0.63	4.1	16.0	188.6	41	-	5900/25
21IB	6.5	N/A	<0.02	0.04	<.01	0.09	8.03	0.40	0.14	<.01	<.01	4.5	32.0	200.7	26	-	6400/24
22IB	6.6	N/A	<0.02	<.01	0.01	0.06	7.32	0.42	0.28	0.06	<.01	4.9		167.0	38	-	5500/24
23IB	6.5	N/A	<0.02	<.01	0.01	0.11	5.46	0.20	0.16	0.02	0.05	4.0		116.9	41	106	5800/24
24IB	6.5	N/A	<0.02	<.01	0.02	0.03	5.90	0.22	0.16	0.02	0.02	4.8		163.9	38	-	5300/23
25IB	6.1	N/A	<0.02	<.01	0.04	0.04	11.27	0.42	0.16	<.01	0.03	4.6		193.1	57	95	5300/19
26IB	6.1	N/A	<0.02	<.01	<.01	0.02	5.10	0.13	0.04	0.04	0.01	4.0		201.0	45	72	4500/22

271B	6.6	N/A	<0.02	0.08	0.01	0.06	6.54	0.14	0.08	0.02	0.02	2.0	180.4	53	-	5800/24
281B	6.1	N/A	<0.02	0.99	0.01	6.68	47.99	0.68	0.82	0.48	8.68	4.5	196.0	57	-	6500/23
291B	6.3	N/A	<0.02	1.37	0.01	0.71	27.45	0.57	1.24	0.11	0.67	4.9	189.0	47	-	6000/24
301B	5.9	N/A	<0.02	0.07	<0.01	0.05	5.99	0.49	0.23	0.01	0.05	4.4	180.0	30	134	5000/22
311B	6.4	N/A	<0.02	0.31	<.01	0.33	12.03	0.73	0.51	0.04	0.31	3.9	202.0	28	74	5400/22

END OF THE DATA

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